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STEEL AND IRON

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BLAST FURNACES, STOVES, ETC., OF THE NATIONAL TUBE WORKS CO., McKEESPORT, PA.

STEEL AND IRON

FOR ADVANCED STUDENTS

BY

ARTHUR H. HIORNS

HEAD OF METALLURGY DEPARTMENT, BIRMINGHAM MUNICIPAL TECHNICAL SCHOOL

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PREFACE.

THE great importance of the subject of Steel and Iron is universally recognised and more careful investigations into the nature and properties of iron and its alloys are being daily carried out, so that a vast accumulation of printed matter is now available in home and foreign journals for those who have the inclination and the leisure to read and study the subject. But such journals are not accessible to the average student, indeed only to very few in their entirety, and the author does not claim to be fully acquainted with the contents of all the different foreign publications, nor does he wish to pose as an infallible authority on the subject. The iron and steel industries have now assumed such vast proportions, especially since they have called to their aid the resources of the physicist as well as those of the chemist and the mechanician, that no one man has yet arisen capable of speaking authoritatively on every branch of the subject, each of which can supply sufficient matter for a lifetime of study without exhausting it. In fact, it is the very immensity of the ground to be covered that has deterred many from attempting to describe it.

The author, being engaged in imparting technical instruction to a large number of students interested in the iron and steel industries, has keenly felt the need of a

text-book, dealing with the more scientific aspects, for the use of such students, and the present work is an attempt to supply such a need. A book of these dimensions can only deal with general principles, but an endeavour has been made to make them as comprehensive as possible, and to state the most recent views of authorities on the subject. A work of this kind must necessarily be in a great measure a compilation, and the author wishes here to express his profound obligation to the Council of the Iron and Steel Institute for permission to quote from their indispensable *Journals*. The following works have also been consulted: Turner's *Iron*, Howe's *Steel*, Phillips and Bauerman's *Metallurgy*, Bauerman's *Iron and Steel*, Greenwood's *Steel and Iron*, Roberts-Austen's *Introduction to Metallurgy*, *Encyclopædia Britannica*, *Journals of Mechanical Engineers and Electricians*, as well as certain American and foreign publications, etc.

Although the title *Steel and Iron* is given to the book, it has been deemed advisable to treat Iron first, since in the manufacture of steel iron is first extracted from its ores and afterwards converted into steel; but the author wishes to convey the impression that steel is now by far the more important body from a commercial point of view, and has largely replaced iron for many manufacturing purposes. This is due to its superior strength and power of resisting external influences. As refractory materials play a very prominent part in furnace construction a brief account of such bodies is given as a guide to the student. A short chapter is also devoted to fuel, as a useful guide in assisting the student to more thoroughly appreciate the advantages of the different fuels used in the various furnaces referred to in the iron and steel sections.

The sub-title "for advanced students" is not intended

to convey the idea that this is a book of a highly advanced character, but that it is not an elementary book for beginners, and is designed to supply the wants of students pursuing a second or third year's course in a college or technical school.

The author desires to record his indebtedness to Mr. C. R. Clark for executing some of the more important drawings, to Mr. J. H. Stansbie for kindly reading the proofs, and to Mr. W. Hawkins for information respecting practical iron casting.

Birmingham Municipal Technical School,
April, 1903.

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CHAPTER I.

INTRODUCTION.

No metal yet discovered possesses anything like the importance of that of iron, and no useful metal is so widely distributed in large masses throughout the crust of the earth as iron. Nature has bountifully provided mankind with abundant supplies of that metal which is so eminently adapted to the wants and requirements of industry. It is not only valuable in its free state, but when in combination with other elements forms alloys having an endless variety of applications. Notwithstanding the enormous sources of mineral wealth with which this country is endowed as regards iron ores, the development of the iron and steel industries has proceeded with extreme slowness, and 100 years ago we were pottering with this invaluable material in what may be termed homeopathic doses as compared with the colossal scale on which we are now dealing with it.

Iron was mined in this country in the time of the Romans, but for centuries afterwards little or nothing was done in iron smelting, and so scarce was the metal that iron articles were classed in the time of Edward III. among his majesty's jewels. The Spaniards, in designing the Armada, calculated on the superior excellence and abundance of

Spanish iron compared with English as an important element of success. In the middle of the eighteenth century four-fifths of our iron was imported from Sweden. It must, however, be borne in mind that all ancient iron was smelted with charcoal, which greatly limited the production, not only from the restricted nature of our timber forests, but also from the fact that the old methods were only adapted to the purer kinds of ore. Dud Dudley introduced the smelting of iron ores with coal and coke in 1620, and slowly from that time the industry increased. The change from charcoal to coke necessitated a more powerful blast, and blowing cylinders of larger dimensions were introduced by Smeaton in 1760 at the Carron iron-works. In 1784 Cort introduced his historic method of puddling in a reverberatory furnace, using coal as fuel for refining pig iron instead of charcoal, as in the old finery. He also invented grooved rolls for rolling the puddled iron, which gave another great impetus to the trade.

The invention of the steam engine was another important factor in the development of iron making. It enabled mines to be sunk to a greater depth, and thus increased our coal and iron supply. The locomotive has also effected remarkable changes in the transport of materials, and is at the present time an essential portion of an ironworks outfit.

The introduction of the hot blast by Neilson in 1828 soon doubled the output of iron from blast furnaces, and is now almost universally employed. Following close on the adoption of the hot blast came the method of collecting the waste gases of the blast furnace and utilising this waste heat for heating the blast itself as well as for other heating purposes. The chief improvements in the blast furnace of the latter half of the nineteenth century are the adoption of the cupola type in place of the old solid brick structures,

the great increase of capacity, the discarding of the fore-hearth, and the mechanical arrangements for charging and dealing with the pig iron and slag. In connection with this may be mentioned the much closer association of the blast furnace with steel-making plant. Another immense stride was made by utilising the waste gases for heating the blast by means of brick regenerative stoves, the regenerative principle of which we owe to Siemens.

With respect to steel, two great names stand prominently forward, viz., those of Bessemer and Siemens, who respectively invented the processes associated with their names. The basic process for steel making was practically solved by Thomas and Gilchrist, who made the first public announcement in 1878. The most prominent feature of the present day is the invention of the tilting open hearth, the contemplated sizes of which may be described as titanic. 50-ton furnaces are now common, and 200-ton furnaces are mentioned for the near future. Steel, of the mild type especially, is ousting iron in many of the departments in which it was formerly considered to hold an impregnable position.

Mechanical testing and chemical analysis were formerly the only means employed in testing and research, but the microscope and pyrometer have immensely added to our knowledge of the nature and properties of iron, and are destined to play a conspicuous part in the future.

CHAPTER II.

REFRACTORY MATERIALS AND FURNACES.

FOR smelting metals a furnace is required, built of, or at least lined inside with, a material capable of withstanding high temperatures without fusing, or softening, or decomposing by the heat to which it is subjected. As a rule the exterior is constructed of ordinary masonry, but the interior is lined with refractory material, the nature of which depends to a great extent upon the character of the operation to be performed. Refractory materials are either used in the natural state, such as silica, alumina, oxide of iron, magnesia, and fire-clay; or they undergo a preliminary preparation before use. In some cases the materials are moulded to the internal shape of the furnace. If they are not of a plastic nature like fire-clay, then clay, tar, or other binding material is intimately incorporated with them, in order to impart the necessary plasticity.

Quartz or Silica.—This substance neither softens nor melts at the highest furnace temperatures, and is therefore a valuable material for internal construction, either when mixed with refractory clay to form silica bricks, or when used alone as a lining for the beds of reverberatory furnaces. Sand is not composed of pure silica, but the small quantities of lime, oxide of iron, and clay usually present are not

objectionable. Dinas rock is a highly refractory substance, occurring in the Vale of Neath, and contains about 97 per cent. of silica, the remainder being lime, oxide of iron, alumina, alkali, and water. From this material, when mixed with 1 to 3 per cent. of lime, bricks are made, which form valuable linings for the roofs of many reverberatory furnaces.

Alumina is quite as infusible as silica, but is rarely found in nature in any great quantity in the pure state. Bauxite is perhaps the most useful, although it contains large amounts of iron oxide and other impurities. It consists of about 3 to 5 per cent. of silica, about 25 per cent. of iron oxide, 50 to 60 per cent. of alumina, and 10 to 15 per cent. of water. It has a dark red colour, but sometimes it is found with very little oxide of iron, when it is white.

Lime and Magnesia.—These are infusible bodies, strongly basic in character, but they form fusible compounds with silica and other acid bodies. This property is utilised in steel furnaces, the interior of which is lined with these oxides, which unite with phosphoric acid forming stable phosphates. Lime and magnesia occur in dolomite, from which material, after calcination, basic bricks are prepared.

Fire-clay.—The refractory bodies already referred to may be combined together in certain proportions, without ceasing to be refractory. Fire-clay is a hydrated silicate of alumina with varying amounts of lime, magnesia, oxide of iron, alkali, etc., and some mechanically mixed silica. The plastic property which clays possess is due to the chemically combined water. In all cases the plasticity disappears when the clay has been baked, and it remains granular and powdery. The clays of the coal-measures, such as those of Stourbridge, are admirably adapted for making fire-bricks, although not pliant enough for pottery. In fact an excess of plasticity is a disadvantage for most

metallurgical purposes, as the bricks would crack at the time of baking.

Ganister is a highly siliceous clay with sufficient plasticity to enable it to be used as a lining for furnaces. It is used for lining the acid Bessemer converter.

Crucibles, etc.—Earthen crucibles are made of fire-clay mixed with sand, burnt clay, or other infusible matter, so as to counteract the tendency which raw clay possesses of shrinking when heated. The bodies thus mixed with the clay expand, or do not contract on heating, having been already shrunk when burnt, and therefore act in an opposite manner to the clay. Such a composition must be able to resist a high temperature without softening, must not be friable when hot, and be capable of withstanding sudden changes of temperature without cracking, as when a white-hot crucible is brought out of a furnace into cold air.

Some crucibles are required to resist the corrosive action of metallic oxides in the material operated upon, and in the ashes of the fuel, so that a crucible should be selected which is best adapted to the special purpose to which it is to be applied.

The component parts of a crucible are first crushed to a fine powder, and passed through a sieve, the fineness of whose meshes will vary with the desired fineness of the grain in the pot, the plasticity being closely connected with the fineness of the particles—at any rate for small crucibles this closeness of grain appears to be indispensable; then the fine powder is mixed with water and kneaded to the right consistence for use. The best results are obtained by using a mixture of different fire-clays, the most infusible being those containing the largest amount of silica and the minimum of oxides of iron and lime. The presence of potash and soda in small quantities sensibly

increases the fusibility, but in small quantities they act advantageously in soldering the particles together. Iron pyrites, which is frequently disseminated through clays, especially those from the coal measures, is perhaps the most injurious constituent. A crucible made from such clay will become indented with small cavities, and even holes, when exposed to a prolonged high temperature. It follows then that the most refractory crucibles are those made from pure clays, the nearest approach to which is presented by some French clays.

The fitness of a clay for making crucibles may be determined by moulding a portion into the shape of a prism, or any form containing sharp edges, carefully drying, baking, and exposing to a high temperature in a covered crucible for some time. If very refractory the test-piece will show no signs of fusion. If the edges are rounded it is a proof of incipient fusion, and if melted, the clay is useless.

Clay vessels of all kinds may be tested to ascertain their power of resisting corrosion by melting in them a mixture of litharge, or red oxide of copper, and borax, and noticing the time this mixture will take to permeate them. Those which resist this destructive action the longest will of course be the best. Many crucibles are by this means eaten away irregularly, showing the necessity of uniformity of grain to resist perforation.

Plumbago or black-lead pots are made from varying proportions of fire-clay mixed with powdered graphite or coke dust. Good graphite is neither altered nor fused by exposure to the highest temperatures (air being absent), so that it is an admirable substance for crucibles. The graphite is powdered, sifted, and mixed with sufficient clay to render it plastic. Good plumbago crucibles, after a careful preliminary annealing, withstand the greatest

changes of temperature, without cracking, and may be heated many times in succession.

When an ordinary small crucible requires to be protected from the corrosive action of metallic oxides, or when small amounts of metallic compounds have to be reduced, the inside is coated with a lining of charcoal. This is done by first mixing the charcoal with sufficient starch, paste, or treacle to make it adhere when pressed. The crucible is then loosely filled with the brasque, and a cavity of the desired size made by boring with a triangular-shaped piece of wood, and then made smooth with a round elongated wooden tool, whose size and shape is apportioned to the capacity of the cavity desired, or the brasque may be plastered on the inside of the crucible by the fingers.

Fire-Bricks.—A fire-brick used to withstand high temperatures must only contain small quantities of the alkalies, which should not exceed 1 per cent. Glenboig, Stourbridge, and Wortley (Leeds) are the leading brands extensively used; these are safe, though of course there are many other fairly serviceable bricks made of brands less in repute.

Ganister bricks are exceedingly valuable for withstanding the very highest temperatures for the crowns of reverberatory furnaces. They do not crack on cooling so much as bricks composed almost entirely of silica. The *Lowood* brick, made near Sheffield, has a very high reputation in this class. Ganister bricks should be set in thin ganister cement. Crowns are best put on dry, and just "slurried" over the top when finished. No fire-brick has a fair chance if set in a clay inferior to itself; but however good the clay, the experienced furnace builder will use as little as possible.

Dinas bricks are practically infusible, and composed almost wholly of silica. The fractured surface presents

a coarse, irregular structure of a light-brown colour. The lime which is added exerts a fluxing action on the particles of quartz, and so causes them to agglutinate.

The following analysis will serve to show the composition of British materials used in furnace construction :—

	Silica.	Alumina.	Ferric oxide.	Lime.	Magnesia.	Potash and soda.	Titanic acid.
Fire-brick :							
Glenboig, -	65·41	30·55	1·70	0·69	0·64	0·55	1·33
Stourbridge, -	73·05	22·40	2·43	0·39	0·54	1·09	—
,, -	77·63	19·48	1·29	0·18	0·31	0·91	—
Newcastle, -	73·30	20·56	1·69	1·55	0·72	2·50	—
,, -	58·00	36·50	1·67	0·58	0·82	2·42	—
Pensher, -	65·10	30·03	2·00	0·45	0·51	2·04	—
Flintshire, -	88·10	4·50	6·10	1·20	—	—	—
Leeds, - -	77·30	19·17	1·43	0·45	0·63	1·20	—
,, -	72·65	23·75	1·75	0·30	0·36	0·90	—
,, -	67·82	25·56	2·00	1·12	0·72	2·47	—
Elland, - -	62·33	35·59	1·25	0·73	0·10	—	—
Ganister bricks:							
Lowood, -	96·32	0·99	0·71	1·28	0·25	0·26	—
Witton, -	94·80	0·89	1·10	2·85	0·32	0·30	—
Dinas bricks :							
Wales, - -	95·16	0·42	0·33	2·96	0·26	0·29	—
						Manganous oxide.	
Burnt Dolomite:							
Raisby Hill, -	5·60	2·35	1·70	56·56	32·18	1·20	—
Ganister :							
Lowood, -	89·55	4·85	1·28	—	0·80	3·52	—
Weardale, -	87·53	9·10	0·64	0·73	0·40	1·05	—

Furnaces.—A hearth, forge or furnace is an arrangement for conducting metallurgical operations by the agency of heat. The inside is generally lined with refractory material, and the outside constructed of ordinary material. All furnaces may be divided into three classes: (1) those without an independent fireplace, such as a blast furnace and a hearth ; (2) those with an independent fireplace, such as a reverberatory furnace ; (3) those in which the material

is separated both from the fuel and from the products of combustion, such as a zinc retort. They may be used with a natural draught, the air being aspirated by means of a chimney, or the air may be forced in by means of a blowing apparatus. In both cases the heat developed depends on the calorific power and weight of fuel burnt in a given time, also on the mode of combustion, for if the combustion is complete the whole of the heat may be utilised. Furnaces may be classified thus:

Hearth.—The smith's hearth may be taken as a type of this class, but some hearths, such as a lime kiln and that used for liquation, are worked by means of a natural current of air.

Shaft Furnaces.—These generally go by the name of blast furnaces, of which those used for smelting iron ores are typical. The vertical kilns for roasting iron ores have no artificial blast.

Reverberatory Furnaces.—In this class the fire is separated from the metalliferous matter by a low brick wall termed a fire-bridge. They are generally worked by means of a natural draught, but an air blast is sometimes used.

Closed Vessel Furnaces.—The vessel may be a crucible, as in melting platinum; or a retort, as in distilling zinc; or a tube, as in liquating bismuth; or a more or less rectangular chest, as in the cementation process for steel.

A *Hearth* is a low furnace in which the material to be operated upon is mixed with the fuel and flux. The heaps, stalls, and kilns for roasting ore are included under this title, as the fuel and ore are mixed, and the action is the same.

A *Shaft Furnace* contains one common receptacle for the materials used. The nature of the ore and fuel employed in a shaft blast furnace will determine the shape. In

roasting iron ores, for example, where a large mass of material has to be expeditiously treated, and where only a moderate temperature is needed, the diameter is greater in proportion to the height than in the reducing furnace, which has a height three to five times the greatest width, because it is essential to have a high temperature in the region where the fuel is largely consumed, and the more fuel there is burnt in a given space in a given time the higher will be the temperature. The fuel employed is coal, coke, and charcoal, because oxides or materials which have been more or less oxidised by a previous roasting, are generally treated in the furnace. In the case of raw coal, it is decomposed by the heat in the upper portions of the furnace, so that by the time it reaches the zone of combustion it is in the form of coke. The carbon is first burnt to carbon dioxide by the action of the blast, but this, coming immediately in contact with highly-heated carbon, is changed to carbonic oxide ($CO_2 + C = 2CO$). This is the chief agent in effecting the reduction of the metallic oxides. A shaft furnace, supplied with air by means of a forced blast, may be theoretically divided into three parts. (1) The upper portion is the region of partial reduction, without melting; carbonic acid is removed from carbonates; any matter of a volatile nature is driven off, and a raw coal is largely coked. (2) The middle portion may, to a great extent, be considered neutral, because the carbon dioxide, formed by the complete reduction of the metallic oxides in the lower part of the furnace, is an oxidising agent, and therefore neutralises the effect of carbon and the reducing gases. (3) The lower portion, where the temperature is highest, is completely reducing. Here the flux and earthy matters, etc., combine to form a fusible slag; the reduced metal also becomes liquid, and alloys with other elements which have been simultaneously reduced, and falls to the

bottom of the furnace in virtue of its specific gravity; the slag, being lighter, floats on the top. Gruner classifies blast furnaces according to the ratio of the maximum diameter to the height, thus:

1. Squat furnaces, in which the height is less than, or equal to, three times the diameter, $\frac{H}{D} < 3$. 2. Ordinary furnaces, in which the ratio $\frac{H}{D}$ varies between 3 and 4. 3. Elongated furnaces, in which the ratio $\frac{H}{D}$ is greater than 4.

The amount of metal produced per day and the consumption of fuel per ton depends on the nature of the ore and the ease with which it is reduced. Some iron blast furnaces have a capacity of upwards of 30,000 cubic feet, and produce 1000 to 2000 tons of iron per week, with the consumption of about 20 to 23 cwts. of fuel per ton of iron. They vary from 85 to 100 feet in height, 20 to 30 feet wide at the boshes, and 11 to 14 feet wide at the hearth.

Reverberatory furnaces are distinguished from the preceding types in being what has been termed "vat" shaped, and having a separate fireplace, which may be an ordinary grate for burning solid fuel, or a special chamber in which fuel is burned so as to produce combustible gases, and termed a gas-producer. That portion of the furnace where the material is being treated has been conveniently termed the laboratory; it is separated from the fire, but not from the flames, by a low wall, termed the fire-bridge, and at the chimney end there is generally another wall, termed the flue-bridge. The chimney is connected with the laboratory by a flue of varying length and more or less horizontal. The chimney serves the two-fold purpose of producing the draught, which is regulated

by a damper, and of carrying off the gaseous products. The height of the roof of the furnace is generally small as compared with the extreme length and breadth, for on it will depend whether the flames act directly or by radiation on the material. The roof generally slopes from fireplace to flue, so that the flame may be reverberated or deflected on to the material. The size of a reverberatory furnace is determined by the kind of material to be operated upon and the temperature required. When ores are simply roasted, a moderate temperature only is required and the area of the laboratory may be five to six times that of the fireplace; but when a high local temperature is desired, the ratio of fireplace to bed may be as 1 : 2, as in the case of a puddling furnace. The atmosphere of an ordinary reverberatory furnace is essentially oxidising, and is modified by the arrangement of the fire on the bars of the grate. If the fuel is kept in a thick layer much carbonic oxide will be produced, which is a reducing gas; but if the layer of fuel is thin, much of the air can readily penetrate through with little change, and the gas produced by the combustion of the fuel is then chiefly carbon dioxide, and the atmosphere is intensely oxidising. This, however, depends on the rapidity of the draught.

Natural Draught.—Natural draught is obtained by means of a chimney. When gases and vapours escape from burning materials they are expanded and therefore tend to rise, because they are specifically lighter than the surrounding atmosphere, and would leave a partial vacuum if the place were not immediately filled with a supply of atmospheric air which is specifically heavier. Now, if a chimney be so tall that the upward currents of gases have time to cool until their density becomes greater than that of the external air, or even equal to it, then the practical limits of height have been exceeded. The pressure pro-

ducing a current through the chimney is equal to the difference in the weight of a column of gas at the ordinary temperature, and of that of an equal column at the temperature of the chimney. The height therefore is regulated by the difference of temperature of the gases inside and outside the chimney, and the weight of such a column will decrease in direct proportion to the rise in temperature, for gases expand $\frac{1}{273}$ of their bulk for every rise of 1° C. Now, the action of a chimney largely depends on the weight of air supplied in a given time; therefore there must be limit to its action, and this limit is stated to be reached when the mean difference of temperature between the external air and the internal gases is about 300° C. For furnaces in which the combustion is very moderate the height need not exceed 35 feet; for iron and copper refining furnaces, about 50 feet is required; and for steam boilers the chimneys are sometimes 60 to 100 feet high.

There is an intimate connection between the draught produced by a chimney and the size of the grate where the fuel is burned. If the grate is small, the draught will be keener for the same size of chimney than when the grate is of larger dimensions. If the draught is too slow, much carbonic oxide is formed; but with a rapid draught the carbon is largely burnt to carbon dioxide. If the bed of fuel is deep, the temperature may become sufficiently high to form carbonic oxide by the reaction: $CO_2 + C = 2CO$. Light, porous, and inflammable fuels, such as charcoal, form carbonic oxide more readily than coal and coke; so that the latter are capable of being used with a greater depth on the grate than with wood and charcoal, without loss of heat by the formation of combustible gases and dust which pass into the chimney.

Forced Draught.—The primitive method was by means of bellows, made of the skins of animals, and having

a pipe for the delivery and admission of air. The skins were inflated by strings pulled by hand, and worked by the pressure of men's feet for the exhaust. Single-acting bellows with a valve were afterwards introduced, and these again were superseded by the double-acting bellows now in use, which yield an uninterrupted stream of air. Another primitive contrivance, known as the water-blast, is described in connection with the Catalan forge for smelting iron ores. Blowing cylinders for producing a stream of compressed air are now generally used for smelting furnaces, such as are described for supplying the air to iron reduction blast-furnaces. In the simple melting of metals, such as pig iron, in a cupola, a rotatory fan or blower is used. Root's blower is largely used for this purpose.

Hot Air.—If the air supplied to a furnace be previously heated, the temperature of combustion may be greatly increased, and as the waste heat of a furnace may be utilised in heating the air, a great economy is thus effected. The regenerative principle of heating was introduced by Siemens, and is now largely used in connection with open-hearth furnaces. The regenerators are chambers of open refractory brickwork, containing a series of passages through which the waste gases from the furnace pass in their journey to the chimney, and thus after combustion give up their heat to the brickwork. When one pair of chambers has been sufficiently heated, the furnace gases are diverted to another pair of chambers, and the previously heated pair then being used for heating gas and air respectively, which traverse them in reverse order, and thus pass over regions of gradually increasing temperatures and enter the furnace at the maximum temperature, thus by their union producing the maximum heat. In order that the spent gases shall not pass into the chimney at a higher temperature than 150° C., it is necessary

to provide about 7 square feet of brickwork for every pound of coal burnt between the two reversals of the currents. Air is also heated by conduction. This is well exemplified by the heating of the blast in iron smelting by means of cast-iron pipes heated externally, the air being forced through the inside, abstracts heat from the walls of the pipe. The same principle is employed in the Ponsard, Bœtius, and Bicheroux furnaces. The regenerative principle for hot air is also employed in hot blast stoves.

CHAPTER III.

FUEL.

By this term is meant substances that may be burned in air to give heat capable of being applied to economic purposes. The two chief elements employed are carbon and hydrogen, the latter in fuels being always associated with carbon. In all fuels containing carbon, hydrogen, and oxygen, the proportion of hydrogen may be equal to, or greater than, but never less than that required to form water with the oxygen. The amount of hydrogen united with oxygen is not available as a source of heat, so that the excess of hydrogen over this amount is called "disposable" hydrogen, and that in combination, the "non-disposable" hydrogen.

The amount of heat a unit weight of a body is capable of yielding when completely burnt is termed its calorific power. The heat is measured either by the number of the units of weight of water raised 1° C., or by the number of units of weight of water evaporated. The latter was proposed by Rankine, and gives numerical results 537 times less than the former. Except in this country, the gram-centigrade unit, termed a calorie, is generally used. This is the heat required to raise 1 gramme of water from 0° to

1° C. The British unit is the amount of heat required to raise 1 lb. of water 1° C. The following table is arranged in accordance with this unit:—

Wood charcoal,	8080
Gas carbon,	8047·3
Artificial graphite,	7762·3
Native graphite,	7796·6
Diamond,	7770·1
Carbonic oxide,	2403
Carbon when burnt so as to form carbonic oxide,	2473
Marsh gas (CH_4),	13063
Olefiant gas (C_2H_4),	11857
Native sulphur,	2249
Amorphous silicon,	7830
Crystallised silicon,	7540
Phosphorus,	5747
Hydrogen,	34462

The number 8080 for wood charcoal signifies that 1 lb. of that body when completely oxidised to carbon dioxide will produce sufficient heat to raise 8080 lbs. of water 1° C.; and so on for the rest. The lower calorific powers of the denser forms of carbon are probably due to the absorption of heat in the mechanical work of breaking up the molecular constitution before the atoms are capable of uniting with oxygen. It will be observed that the densest form of carbon (diamond) yields the lowest calorific power. The calorific power of a fuel containing carbon, hydrogen, and oxygen, would be the sum of the calorific powers of the carbon and that of the disposable hydrogen.

The calorific power of a compound of carbon and hydrogen such as C_2H_4 may be calculated thus:—

$C_2 = 24$
$H_4 = 4$ } The atomic weight of carbon being 12 and that of hydrogen 1.
28

Then if 1 lb. be taken, $\frac{6}{7}$ will be carbon and $\frac{1}{7}$ will be hydrogen.

$\frac{6}{7}$ of 8080 = 6925·7

$\frac{1}{7}$ of 34462 = 4923·1

Calorific power = 11848·8

Many hydrocarbons yield a less calorific power by experiment than by calculation, probably owing to the heat absorbed in their decomposition. Experiment and calculation only perfectly agree when the two elements are mechanically mixed, and not when they are chemically combined.

The instrument used for determining the calorific power of a body is termed a calorimeter. It consists essentially of a vessel in which the fuel may be so burnt that the heat produced is imparted to a given weight of water, the increase in temperature of which serves to indicate the calorific power.

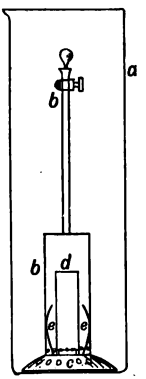


FIG. 1.

(*a*) The apparatus (Fig. 1) consists of a tall glass cylindrical vessel *a* capable of holding 60,000 grains of water. At a given distance a mark is scratched on the outside to indicate 29,010 grains of water, which equals 967 × 30 (the former figure being the latent heat of steam in degrees F. and the latter the weight of fuel taken); (*b b*) a copper vessel is fitted at the top with a stop cock; *c* a perforated stand, into the socket of which the copper crucible *d* fits. This stand has three springs *e* for keeping the cylinder *b* tightly fixed in the socket.

To determine the calorific power of a given fuel, carefully dry a quantity of finely powdered potassium chlorate, and nitrate in separate dishes. Also a quantity of the fuel very finely powdered should be carefully dried. Weigh

out 30 grains of the dried fuel, 225 grains of potassium chlorate, and 75 grains of the nitrate; well mix and introduce into the perfectly dry copper tube of what is known as Thompson's or Wright's calorimeter; ram it moderately tight; insert a small piece of "fuse" (prepared by soaking cotton wick in a solution of nitre and drying it), and place the tube in the stand ready for the experiment. Now take the temperature of the water in the large vessel; light the fuse; cover with the bell tube, taking care that the tap is closed, and put the whole in the water before the ignited fuse has had time to burn down to the mixture. When the combustion appears complete, open the tap so that the water may absorb the residual heat in the tube, and again take the temperature of the water. The increase of temperature, plus 10 per cent. added for loss, gives the evaporative power of the fuel.

EXAMPLE.

Temp. of water before the experiment	=	55° Fahr.
„ „ after „ „	=	66° „
„ produced by the combustion,	=	11
Plus 10%	=	1·1
Total evaporative effect,	=	12·1

i.e. 1 lb. of the coal on perfect combustion will generate 12·1 lbs. of steam.

The Berthelot-Mahler bomb calorimeter (Fig. 2) has been specially devised for calorimetric measurements. It consists of a steel shell A of about 40 cubic inches capacity, nickel plated on the outside and enamelled on the inside. The top is closed by a screw cap provided with a cock *b* for admission of compressed oxygen. A platinum rod attached to the cap supports a platinum cup *c*, in which the fuel to be tested is placed, and the ignition is effected by

the heat of the wire *d*, which conveys an electric current. The combustion and products of combustion being confined to the inside of the bomb, the heat is transmitted through its walls to the water in the vessel E surrounding the

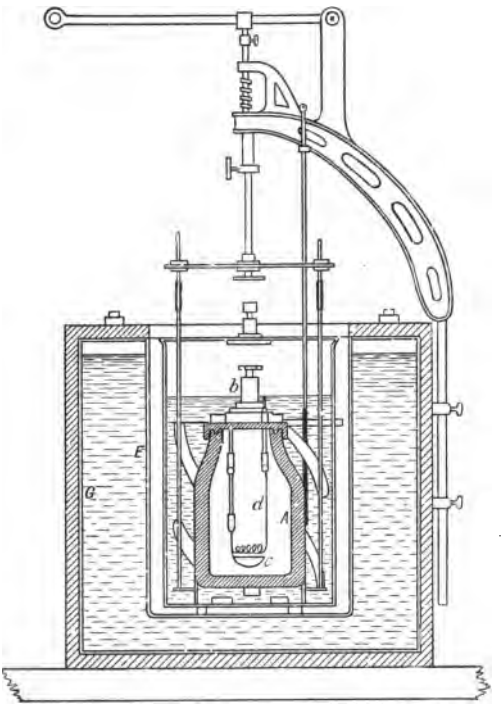


FIG. 2.

bomb. In order to get a uniform temperature a helical agitator is employed as a stirrer. An outer vessel G, covered externally with felt, also contains water and is provided with a thermometer for registering the initial and final temperatures. For solid or liquid fuel a gramme is generally taken. For determining the calorific power of a

gas of constant volume, the bomb is exhausted of air, filled with the gas, again exhausted, finally refilled at the atmospheric pressure and the necessary oxygen forced in. Ignition is effected as before, and the heat absorbed by the water.

Calorific Intensity.—This is the pyrometric degree of heat obtained when a body is completely burnt, and is theoretically the actual temperature of the products of combustion. It is based on the assumption that the products of combustion have constant specific heats for all temperatures and that they absorb all the heat produced, which is not the case. Heat is lost by conduction, radiation and imperfect combustion, and dissociation also limits the temperature.

Suppose 12 grains of carbon to unite with 32 grains of oxygen to form 44 grains of carbon dioxide, or 1 grain of carbon to unite with $2\cdot\dot{6}$ grains of oxygen to form $3\cdot\dot{6}$ grains of carbonic acid, thus—

$$C + O_2 = CO_2,$$

and the whole heat produced absorbed by this CO_2; that the pressure is constant and the specific heat of $CO_2 = \cdot2164$;

$$\text{then the calorific intensity} = \frac{8080 \times 1}{3\cdot\dot{6} \times \cdot2164} = 10174.$$

Now suppose the carbon burnt in ordinary air instead of oxygen. In this case nitrogen has to be heated without yielding anything to the calorific power. 1 part of oxygen in air is mixed with 3·35 parts of nitrogen, so that the weight of nitrogen to be heated when 1 part of carbon is converted to carbon dioxide is $2\cdot\dot{6} \times 3\cdot35 = 8\cdot93$. The specific heat of nitrogen is ·244.

$$\text{Calorific intensity} = \frac{8080 \times 1}{(3\cdot\dot{6} \times \cdot2164) + 8\cdot93 \times \cdot244} = 2718.$$

The calorific intensity of carbonic oxide (CO) when burned in oxygen according to the equation,

$$CO + O = CO_2,$$

is 7073. One part of CO forms 1·57 parts of CO_2, then the

$$\text{calorific intensity} = \frac{2403}{1{\cdot}57 \times {\cdot}2164} = 7073,$$

$$\text{and in air} = \frac{2403}{(1{\cdot}57 \times {\cdot}2164 + (1{\cdot}91 \times {\cdot}244)} = 2984.$$

The calorific intensity of hydrogen when burnt in oxygen is computed on the assumption that the water produced is in the liquid state; but it is in the form of gas, therefore the condensation of that gas to a liquid would evolve 537 units of heat. Also in raising the water from 0° to 100° and from 100° to the temperature obtained, we have first water with a specific heat of 1, and afterwards steam with a specific heat of ·48, and $(1 - {\cdot}48) \times 100 = 52$; and as 1 lb. of hydrogen produces 9 lbs. of water the above amounts have to be multiplied by 9, thus $(52 + 537) \times 9 = 5300$. The calorific intensity of hydrogen is therefore

$$\frac{(34462 - 5300)}{9 \times {\cdot}48} = 6750.$$

When the hydrogen is burnt in air the calculation is thus:—

$$\frac{34462 - 5300}{(9 \times {\cdot}48) + (26{\cdot}8 \times {\cdot}244)} = 2685,$$

26·8 is the amount of nitrogen in the quantity of air required to yield the requisite oxygen (8 parts) for 1 part by weight of hydrogen.

Pyrometry.—By this term is meant the measurement of high temperatures, and the instrument employed for this

purpose is termed a pyrometer. Pyrometers have been constructed on the following principles :—

1. By contraction in the volume of a body.
2. By change of volume in gases, liquids and solids
3. By dissociation of chemical compounds.
4. By simple fusion of metals, alloys, clays, etc.
5. By conduction of heat by metals.
6. By radiation.
7. By thermo-electric methods.
8. By electric resistance.
9. By optical methods.
10. By calorimeter methods.

1. Wedgwood's pyrometer is based on the shrinkage of dehydrated clay. Spherical pieces with one side flat and of equal size are employed. He assumed that the shrinkage was proportional to the temperature, but this is not strictly so, and the method is only of advantage where relative temperatures are required to be roughly measured.

2. Gauntlett's pyrometer is based on the principle of the different rates of expansion of different substances. A metallic rod is placed in a hollow cylinder of refractory material, and the difference of expansion is registered by causing the bar in expanding to move an index of infusible material within the cylinder.

Deville and Troost applied the principle of the air thermometer to the measurement of high temperatures. Into a flask of porcelain of 300 c.c. capacity, having a long neck, is placed a little iodine. It is then inserted in the hot space until the iodine is vaporised and the air nearly expelled. The neck is then sealed with a blowpipe and the flask cleaned and weighed when cool. The neck is then broken under water, and the flask with the water which has entered again weighed ; it is then completely filled with water and reweighed : finally the flask is weighed when

empty. From these weighings the amount of residual air which was not expelled by the iodine is computed, as well as the capacity of the flask, and the amount of iodine at the time of sealing. Now knowing this amount of iodine and the volume it occupied at the same moment the temperature may be computed according to Boyle's law.[1]

4. *The principle of the simple fusion of bodies* of known melting points, such as the common metals and certain alloys, is the simplest method of measuring temperatures where only approximate results are needed. This method is used for determining the temperature of the hot blast.

The Seger Cones or pyramids are made of mixtures of various silicates in different proportions, so as to vary the temperature at which they melt, and by this means temperatures varying from 600° to 1700° C may be determined. These cones are numbered and by means of a table supplied by the inventor the corresponding temperature is given.

5. *Conduction of heat* has been applied to the measurement of the temperature of a furnace by inserting in it one end of an iron bar, and at the other end of the bar is a hole in which a mercurial thermometer is placed. This method is only approximately correct. Carnelly and Burton described a new form of pyrometer on this principle, to the Chemical Society, in 1884. "If a current of water of known temperature be allowed to flow at a constant rate through a coiled metallic tube, placed in a space, the temperature of which is to be ascertained, the increase in the temperature of the outflowing water will be the greater the higher the temperature of the space."

7. *Thermo-electric Method.*—This appears to be the most reliable pyrometric method yet devised, and of thermo-

[1] *Watt's Dictionary*, Vol. III., page 20.

couples the one introduced by Le Chatelier is among the best. A sectional view with the constituent parts of the apparatus is shown in Fig. 3. It consists of a wire of platinum and a wire of an alloy of platinum with 10 per cent. of rhodium either twisted or soldered together. When this thermo-electric junction is heated a current of electricity is generated, and the current is sent through the coils of a reflecting galvanometer, the amount of the deflection of the mirror connected

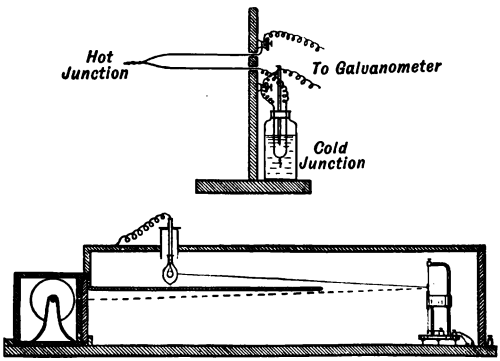


FIG. 3.—THERMO-ELECTRIC PYROMETER.

with the magnetic needle being proportional to the heat applied to the junction. The instrument is calibrated by taking certain well-known temperatures, such as the melting point of silver, boiling point of zinc, sulphur, etc. The usual arrangement consists of two light boxes, the larger of which contains a D'Arsonval galvanometer (Fig. 3A) with a suitable arrangement of lenses and mirrors. The smaller box contains a drum which is made to revolve by contained clockwork, once in a given period. It also is fitted with a slit and shutter. A ray of light is thrown by means of a lamp on to the mirror of the galvanometer, and is projected thence on to surface of the drum, which

contains sensitised paper. The galvanometer is connected by wires to the thermo-junction inserted in the hot place, the temperature of which it is desired to obtain. The amplitude of the deflection indicates the temperature, and a continuous curve is traced on the photographic paper. For fuller information the reader should consult Roberts-Austen's work on Metallurgy and *Journal of Iron and Steel Institute*, 1892-1894.

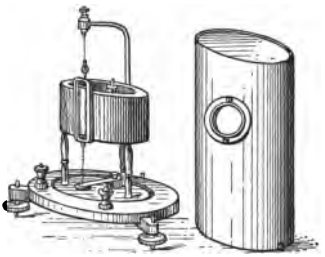


FIG. 3 A.—D'ARSONVAL GALVANOMETER.

8. *Electric Resistance Method.*—Siemens' electric resistance pyrometer is represented in part in Fig 4. It consists of a platinum spiral (*a*) of known resistance, wound on a cylinder of fire-clay, and enclosed in a case of platinum or copper, according to the temperature to be measured. The two ends of the coil are connected by thick platinum wires with two thick copper wires, at the part which is less strongly heated. These wires are insulated by pipe-clay tubes (*bb*) and communicate with the measuring instrument by which the resistance is measured. The electric resistance of platinum is increased fourfold by a rise in temperature from 0° to 1650° C. The portion (*cd*) which is exposed to the highest temperature of the furnace is encased in wrought iron or platinum, and the outer portion (*ce*) is enclosed in an iron tube. The outer tube is shown in *A*, and the resistance arrangement in *B*.

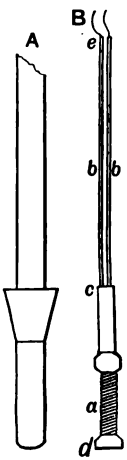


FIG. 4.

9. *Optical Method.*—The pyrometer of Mesuré and Nouel depends on the partial rotation of polarised light by a

quartz plate; the rotation varies with the intensity of the light, and by measuring this the temperature of the substance which emits the light can be determined. A quartz plate is placed between the polarising and analysing prisms, the latter being turned until a definite neutral tint between green and red is produced. The angle is measured and the temperature determined by reference to a prepared table.[1]

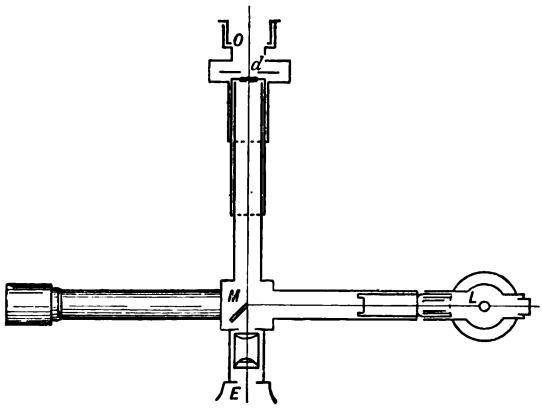


FIG. 5.

The Cornu—Le Chatelier pyrometer consists of a telescope associated with a standard of comparison oil lamp. The flame is projected upon a mirror fixed at an angle of 45° and placed internally across the junction of the lamp tube branch with that for sighting the incandescent object. The intensity of the luminous beams from the lamp and that from the furnace, whose temperature is to be measured, is equalised, and the degree of adjustment required enables the temperature to be determined. Fig. 5 shows a plan of the pyrometer; *L* is the lamp, the beams from which are projected on to the mirror *M* by means of a lens and

[1] *Introduction to Metallurgy*, Roberts-Austen, p. 159.

reflected along the branch containing the eye-piece *E*. The object glass *O* has a diaphragm or stop *d* in front. In cases of a very dazzling light a tinted glass may be fixed in the mounting *E*. Before the eye-piece there is fixed a monochromatic red-tinted glass which serves for the purpose of observation of the object to be tested. Near the oil lamp there is fixed a rectangular set of stops similar to those before the lens *O*. They serve for fixing the height of the oil flame, and for intercepting the extraneous rays. In order to measure the intensity of the heat of the incandescent body, the height of the flame should remain constant, and the luminous beam from the lamp should be divided into two equal parts by the edge of the mirror *M*. This can be obtained by turning the lamp on its mounting.

In order to take a measurement the object glass is turned towards the furnace, or other incandescent surface to be tested, in such a way that its image is cut in equal divisions by the edge of the mirror, and is thus brought into contact with the image projected from the light of the oil lamp. The opening of the shutter diaphragm aperture, and the variation of the intensity of the beam projected from the incandescent surface, is effected by turning the screw knob on the object telescope, so that by this means the equality of intensity of the two images is established.

If n is the number of divisions read upon the graduated scale fixed on the tube of the object glass, and indicating the degree of adjustment of the shutter diaphragm of the lens *O*, and n' is the number of divisions obtained on sighting the source of light from the standard lamp, the intensity of heat sought for will be obtained by the formula:

$$\left(\frac{n'}{n}\right)^2 = 1 \text{ (intensity of heat).}$$

In other words the intensity is equal to the inverse ratio of

the superficies of the opening of the shutter diaphragm fronting the lens *O*.

10. *Calorimeter Method.*—Pouillet exposes a ball of copper or of platinum of given weight to the heat of the furnace, and then rapidly transfers it through a clay tube to a vessel containing a known weight of water, at a known temperature t. From the increase in temperature of the water $t' - t$, the temperature of the furnace is calculated. The mode of calculation is as follows:

$$T = \frac{W \times (t' - t)}{w \times s}.$$

Coal is of vegetable origin, and resembles wood and peat in character the more modern the formation in which it is found. It may be divided into three distinct classes—Lignite, Coal and Anthracite—the first being the least altered and the last the most completely changed. As we descend the series, the oxygen diminishes and the carbon increases; but the chief characteristic of different kinds is the ratio of hydrogen to oxygen, and the carbon left on distillation in a closed vessel. In lignites the ratio $\frac{O}{H}$ varies from 6 to 5, and the coke is below 50 per cent. In coal the ratio $\frac{O}{H}$ varies from 4 to 1, and the coke from 50 to 90. In anthracite the ratio $\frac{O}{H}$ is 1 or less than one, and the coke exceeds 90 per cent.

Coal proper is distinguished from lignite by a more pronounced black colour, greater density, more friability, more laminar structure, absence of woody fibre, a greater yield of coke, less water in the products from distillation, and that rather basic than acid, and the absence of the disagreeable odour of lignite when burning. In the natural state coal contains but little water, and is less hygroscopic in air than wood or lignite.

Coal, by its appearance, properties, and composition, forms a continuous series from lignite to anthracite, with no definite line of separation. The proportionate yield of coke is from 50 to 90 per cent., and the elementary composition as follows:—

Carbon,	75 to 93	
Hydrogen,	6 to 4	
Oxygen,	19 to 3	
	100	100

The first column belongs to coal bordering on lignite, the second column to that approaching anthracite. Between these extremes are varieties with intermediate properties.

Coal may be conveniently subdivided into five classes, based on the yield of coke and action in the fire: 1. Long flaming coal; 2. gas coal; 3. forge coal; 4. caking coal; 5. lean or anthracitic coal.

Long Flaming Coals, approximate in properties to lignite on the one hand and to caking coals on the other. They are non-caking, and give a long smoky flame when burning. They occur abundantly in Scotland, also in Derbyshire and Staffordshire. The calorific power is 8000 and upwards.

Gas Coals are only moderately caking, some varieties yielding a very friable coke. These give off much volatile matter when heated, and yield a long smoky flame. The calorific power is about 8500, and they give off about 20 per cent. of gases.

Forge Coals.—These are moderately hard and dense, with a black colour and fatty lustre. The calorific power is about 9000. They burn with a fairly long smoky flame, generally yield a good compact coke, and evolve 15 to 16 per cent. of gases.

Caking Coals with Short Flame.—These are the best caking coals, they yield a hard, dense, compact coke, and

liberate 12 to 15 per cent. of gases. The calorific power is about 9500.

Anthracitic Coals.—These burn with a short flame, and form a connecting link between caking coals and anthracite proper. The calorific power is about 9300. They occur abundantly in South Wales and in Pennsylvania.

Anthracite is compact, of a deep black colour and a lustre bordering on the metallic; it is brittle, breaks with an uneven or conchoidal fracture, has a high degree of hardness and cohesion; it inflames and burns with difficulty, giving an almost smokeless flame. Some varieties easily decrepitate. It yields neither water nor bitumen in sensible quantities when heated, and the fragments neither fuse nor change their lustre nor cake together. It may be looked upon as the most completely changed form of vegetable matter in its conversion into coal.

Petroleum.—In various parts of the earth are found combustible bodies similar to "petroleum," which, when solid contain a large amount of ash. They are solid, liquid, and gaseous hydrocarbons, rich in carbon. Marsh gas and olefiant gas are gaseous; petroleum proper is liquid and the asphalte of Mexico is a kind of solid petroleum which fuses below 100° C. An analogous compound to asphalte is the noted "boghead" of Scotland, which is richer in bitumen than ordinary coal. When the earthy matter diminishes to the proportion present in ordinary coal, it takes the name of "cannel" coal. The natural mineral called jet occupies an intermediate place between coal and petroleum. It is a bituminous lignite, and disengages, when heated, 55 to 60 per cent. of volatile matter.

Natural Gas.—In certain parts of the United States, chiefly in Pennsylvania, West Virginia, and Ohio, natural gas issues from the earth, proceeding from strata 800 to

COMPOSITION OF VARIOUS FUELS AFTER COMPLETE DRYING (Gruner).

Name	Percentage of composition.			Proportion of oxygen per 1000 of carbon.	Proportion of hydrogen per 1000 of carbon.	Ratio of $\frac{O}{H}$	Charcoal or coke obtained by heating the dry material in form of powder.	Nature of the charcoal or coke obtained.	Calorific power.
	Carbon.	Hydrogen.	Oxygen.						
Cellulose, -	44·44	6·17	49·39	1111	139	8	28-30	Pulverulent.	—
Wood, - -	50-51·75	6-6·30	44-41·95	880-800	120-122	7	30-35	Do.	—
Peat, fossil Wood, -	58-63	6-5·5	36-31·5	620-500	100-85	6-5	35-40	Do.	3000 to 5000
Lignites, - -	65-75	6-4	29-21	450-280	92-55	5	40-50	Do.	5000 to 7000
Coal, poor, with long flame, -	75-80	5·5-4·5	19·5-15	260-190	75-60	4-3	50-60	Pulverulent, slightly fritted.	8000
Coal, rich, with long flame, -	80-84	5·8-5	14·2-10	180-120	70-60	3-2	60-68	Caked, very tender.	8500
Coal, ordinary, rich, - -	85-89	5-5·5	10-5·5	130-60	65-56	2-1	68-74	Caked, moderately compact.	9000
Coal, rich, with short flame, -	88-91	5·5-4·5	6·5-4·5	70-50	62-50	1	74-82	Caked, very compact.	9500
Coal, anthracitic, - -	90-93	4·5-4	5·5-3	50-40	50-35	1	82-90	Fritted or Pulverulent.	9300
Anthracite, -	93-95	4-2	3-2	40-25	35-30	1-0·75	90-92	Pulverulent.	—
Petroleum, -	80-85	15-14	3-1	30-15	185-175	0·20-0·10	—	—	—

2000 feet below the surface, and when bore-holes are sunk, the gas rises at a pressure of 150 lbs. per square inch. This gas is used for illuminating and heating purposes. The composition per cent. varies within the following limits: 60 to 80 CH_4, 5 to 20 H, 1 to 12 N, 1 to 8 C_2H_6, 0·2 C_2H_4, and 0·3 to 2 CO_2. It has a calorific power of 14,000 to 15,000. One gas well alone in Ohio has been blowing for 30 years without any apparent diminution.

PREPARED FUEL.

Certain fuels, as soft peat, coal dust, etc., are unsuitable for use in the natural state, but may be prepared by compression, as in peat; or caked, as in coal dust, by mixing it with coal tar, pitch, or other cementing material. Wood and peat have their calorific powers increased by artificial drying.

Wood Charcoal.—When wood is heated to a temperature of 400° out of contact with air; water, acetic acid, tar, carbon dioxide, carbonic oxide, hydrogen, marsh gas, etc., are given off, and a black, sonorous, hard mass of charcoal is left. At a lower temperature—270° to 300° C. it is more or less brown, feebly sonorous, but more tenacious than black charcoal. Charcoal always retains some oxygen and hydrogen, but the amount is less the higher the temperature employed in its production. On an average it contains 90 per cent. carbon, 3 per cent. hydrogen, and 7 per cent. oxygen. The specific gravity varies from 0·28 to 0·54, according to the nature of the wood and the temperature employed. The ash left after combustion is 3 to 4 per cent., and of the same character as that from wood.

Peat Charcoal.—The shape of the peat is preserved like that of wood when heated in closed vessels. It is black in colour, porous, soft when prepared from peat in its native state, and more compact and dense when prepared from

compressed peat. It, like wood charcoal, retains some volatile elements.

When steam is passed over red-hot charcoal,—hydrogen, carbonic oxide, carbon dioxide, and a little marsh gas are formed.

Making Charcoal in Piles.—The ground should be dry, well sheltered, and near a water supply. The bed is slightly inclined from the circumference to the centre. One or three stakes, long enough to reach above the upper extremity of the intended mound, are first driven in the ground in the centre of the circle. Around this the wood,

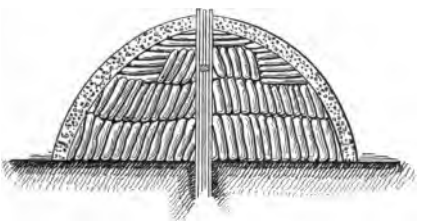


FIG. 6.

cut into suitable lengths, is packed as closely as possible, being placed in a vertical or horizontal direction, and all irregular spaces filled up with small twigs. The wood is then encircled and covered with branches, and the upper portion is covered with turf and charcoal dust, leaving a certain part open at the base for the escape of aqueous vapour during the first stage. The space between the three stakes is filled with readily-inflammable wood, which is ignited to start the operation. The wood in the central part of the pile is charred first, then covered up, the combustion proceeding from top to bottom and from the centre to the outside of the heap. Vents are made at suitable intervals, commencing at first near the top, and closed when the carbonisation in that region is complete, which is judged by the pale blue colour of the smoke (Fig. 6).

2. In some cases rectangular piles are used; in others the charring is effected in kilns and in ovens. The heat by which the carbonisation of wood is effected in piles is produced more by the combustion of charcoal itself than by the burning of the products of carbonisation. The yield varies with the nature of the wood, its age, dryness, and the temperature and mode of charring. By volume the yield varies from 50 to 75, and by weight from 15 to 28 per cent. Peat may be carbonised in much the same way as wood—in piles, in kilns, and in ovens—but it is not suitable for most metallurgical purposes.

COKE.

Coke is obtained when coal is strongly heated, in a closed space or vessel, with a limited supply of air. It may be porous and light, or dense and compact; it is sometimes soft and tender, at others, hard and resisting. The colour varies from black to grey, the lustre being in some cases dull, in others bright and almost metallic. The quality depends on the nature of the coal and the mode of coking. Nearly all coals contain iron pyrites (FeS_2), and a part of the sulphur remains in the coke. The coke from caking coal has the appearance of a porous, partially melted mass, which is grey in colour, with a semi-metallic lustre. The coke from flaming coal is lighter and more friable. The rapid carbonising of a small charge gives a lighter and more friable coke than the slow baking of a heavy charge. Dry coke with little ash is lighter than water. It is hygroscopic like charcoal, but in a less degree. Coke is less inflammable and less combustible than charcoal, but produces a higher temperature on burning.

Coking in Piles.—Coking is effected in circular and rectangular piles, like charcoal. A rough chimney of loose

bricks is first constructed, 6 feet high, capped with a damper, and the coal arranged around it, making a mound 30 feet in diameter at the base. The whole is then covered with wet slack, except a space around the bottom. Ignition is effected by placing live coals on one side of the chimney, near the top, and continued by opening vents in different parts, as in charcoal burning. The coking is completed in about six days

Coking in Kilns.—Two parallel walls (AA, Fig. 7), 5 feet high and 8 feet apart, lined with fire brick, are first built with a series of openings (BB), 2 feet apart, and the same distance from the floor, so arranged that those on one side are opposite to those in the other wall; and from each of

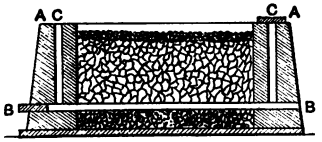


FIG. 7.

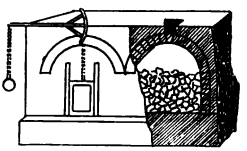


FIG. 8.

these ascends a vertical flue (CC) Any of these flues may be stopped by closing with a tile, so as to divert the current in any given direction. To charge the kiln, one end is bricked up, wet slack is wheeled in, spread in layers and stamped down, reaching nearly to the level of BB. Wood stakes are now placed across, the ends reaching into the corresponding opening in the opposite wall. The coal is then wheeled in, watered, stamped down, the other end bricked up, and the whole covered with loam. The stakes are now withdrawn, and the kiln lighted by inserting inflammable sticks. The charring is completed in about eight days. The whole is allowed two days to cool, and the coke is then withdrawn.

Coking in Ovens.—The beehive oven (Fig 8) is a somewhat circular chamber of brickwork with an arched roof,

having a chimney opening at the top for the escape of the products of combustion and vapours. The cavity is about 9 feet to 10 feet in diameter, and 3 feet to 4 feet high. The charge is introduced through a doorway in front, about $2\frac{1}{2}$ feet square, through which the charge is also withdrawn. These ovens are generally built in two rows back to back, with a charge of three tons in each, which reaches up to the springing of the dome of the roof. When the charging is complete, the doorway is loosely

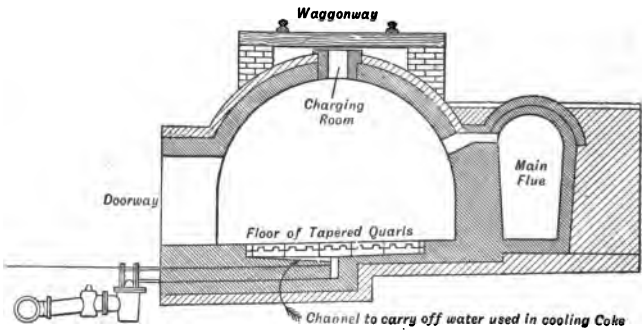


FIG 9.

filled up with bricks through the openings of which the air can pass. Supposing the oven to be hot from a previous charge, in three hours the lower holes are closed, and in twenty-four hours the upper ones are closed. The oven is now allowed to remain twelve hours with the chimney open. When the flame ceases, the damper is closed, and the oven allowed forty-eight hours to cool. The charge is then withdrawn by means of a large shovel suspended by a crane, and the hot coke quenched with water. There is a partial combustion inside the oven so that some of the coke is burnt.

Jameson's Coke Oven is represented in Fig. 9, converted from the ordinary beehive form, for the recovery of volatile

products. The difference between a Jameson oven and one of the usual type consists in the use of a false bottom over a closed bottom below it, and in the removal by aspiration, from between those bottoms, of the gases given off from the coal as the heat travels from the top downwards. Mr. Jameson lays stress upon the fact that in coking coal, by the agglomeration of particles, a species of crust or sealed diaphragm is formed in the charge of coal, which acts as a shield against the passage of air or burnt gases from the upper part of the oven, towards the reduced pressure in the lower part, and at the same time imprisons the gases formed below it, so as to facilitate their removal by the aspirator. Another point to which he attaches great importance is, that in the progress of coking the suction applied to the oven itself should be varied within somewhat wide limits; that is to say, that when the gas is forming near the top of the oven, and is to be drawn through a mass of unheated coal 2 feet or 3 feet thick, there should be a suction equivalent to 2 or 3 inches of water pressure to overcome this resistance, and when the charge in the oven is nearly coked throughout and the gas is formed near the oven bottom, then the suction should be diminished to a pressure perhaps of half an inch of water. The suction, he also points out, should be regulated in reference to the chimney draught, which is, of course, a counteracting influence operating with different force as the oven is more or less closed to the external air. The variation of suction he proposes to make once a day, or at most once in twelve hours, by means of a regulator. Another point of importance is the construction of the oven bottom. The true bottom should be as well secured as possible against ingress of air, and the false bottom should be so constructed as not to allow passage for small coal, and yet sufficiently open so as not to become choked up with

hardened deposits arising from the carbonising of the oil and coal dust.

In the more recent forms of coke oven air is not admitted into the coking chamber, but into side flues, so as to burn the gases outside the oven and thus prevent loss of coke. Moreover, the waste gases are completely burnt, and the heat utilised in heating the oven instead of allowing them to escape, as in the beehive oven. Of this type the Appolt. Coppée, Carvé, and Otto may be mentioned.

Appolt's Oven.—Eighteen vertical retorts of brickwork are built in two rows of nine each, the whole being contained within four brickwork walls. Each retort is rectangular in plan, surrounded by an air space 8 to 10 inches wide. The retorts (Fig. 10) are tapered, measuring 1 foot 1 inch by 3 feet 8 inches at top, and 1 foot 6 inches by 4 feet at base, and 16 feet high. Each retort is provided with a cast-iron door at the bottom, opening into an arched vault, into which the coke is dropped at the conclusion by opening this door. The air spaces surrounding each retort communicate with one another, forming one large divided chamber, which communicates with the inside of the retorts by openings in the brickwork. It is in this divided chamber that combustion of the products of decomposition of the coal takes place, air being admitted through holes in the outer sides of the kiln. By this arrangement a very great heating surface in proportion to the capacity of the oven is obtained, with a very high efficiency in coke produced. The oven is charged with coal at the top, and the time of one operation, starting with hot retorts, is about twenty-four hours. The charge is 1 ton 5 cwt. for each chamber. The great drawback seems to be the high initial cost, which is double that of a horizontal oven, and it is also difficult to repair when out of order.

Coppée's Oven (Fig. 11).—This is constructed, like the Appolt oven, for heating by the combustion of the waste gases in external flues, but the main axis of this oven is horizontal. It is only used for finely divided and washed coal, its chief advantages being rapid coking and an increased yield. Some coals that are not sufficiently bituminous for coking in an ordinary oven may be coked in the Coppée oven. They are usually built in a series of 30 or 40 and

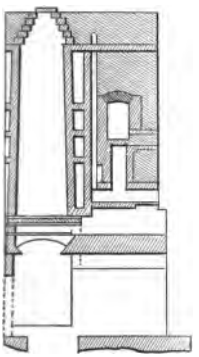


FIG. 10.

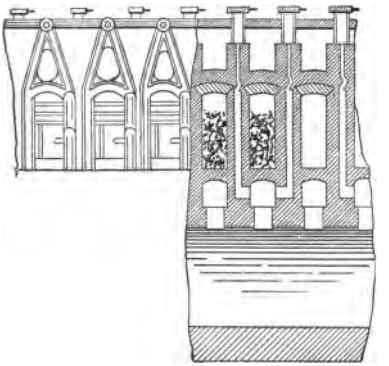


FIG. 11.

worked in pairs. Each oven is 30 feet long, 18 to 24 inches wide, and 4 to 6 feet high, and contains twenty-eight vertical flues leading from the top, through the partition wall common to two of the ovens, to the horizontal flues that pass underneath the chamber in the direction of their length. In these horizontal flues, the gases from a new charge of coal mix with those from another oven in which the coking is nearly completed, and air is admitted through three small openings. After combustion, the flame passes to a bottom flue, giving up a portion of its heat to the bottom of the oven. When the coking is complete, the charge is pushed out by a ram and quenched with water.

Carvé's Oven.—This excellent oven (Fig. 12), has the reputation of producing high-class coke, and of being also well adapted for the recovery of the by-products—tar and ammoniacal liquors. Each oven is a long, narrow and high brickwork chamber, A, resembling that of Coppée, with horizontal flues penetrating the side walls, as shown in dotted outline, BB. These flues communicate with two horizontal flues, CC, running under the floor of each chamber. The products of combustion from the fireplace, E, pass through CC, and then ascend to the uppermost of the side

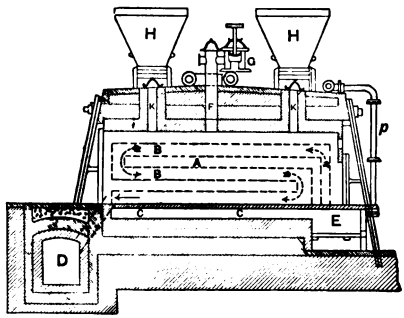


FIG. 12.

flues, BB. From thence they traverse backwards and forwards along the sides of the chamber, finally passing into the flue, D, and thence into the chimney. The products of carbonisation are drawn off by an exhauster through F and the valve G into condensers, where the gases are freed from the ammoniacal liquors and tarry oils with which they are associated. The gases are then brought to the fireplace, E, by a pipe, *p*, and ignite as they pass over the burning fuel. The resulting flame then traverses the bottom and sides of the oven as described above.

In a more recent oven the fireplace is dispensed with and the oven heated entirely by the return gases, air for the

combustion being forced in through a special pipe. In the Simon-Carvé oven the air is previously heated to 500° by contact with the flues conveying away the spent gases to the chimney. The air is not admitted into the bottom flue in sufficient quantity for complete combustion of the gas, and a further supply of hot air is admitted into the side flues for complete combustion. Each oven is about 24 feet long, 6 feet 6 inches high, and 20 inches wide, and takes a charge of about 4½ tons of coal.

The coal for coking is charged through the hoppers, HH. When the charging is complete, the passages, KK, are closed, and the doors closing the ends of the ovens carefully luted to prevent admission of air. This prevents loss of coke by combustion at the surface of the charge, and 15 per cent. more coke is obtained than is produced in an ordinary bee-hive oven.

Semet-Solvay Coke Oven.—This oven is now extensively used for coke making. It is 30 feet long, 5 feet 6 inches high, and 15 to 20 inches wide, depending on the kind of coal to be coked. It is well suited for coking inferior caking coals, works with great rapidity, and cokes a charge of 4 to 5 tons in 24 hours. It is somewhat similar to the Carvé oven in appearance, has superimposed horizontal flues, and continuous heat recuperation. The sides are made extremely thin, the tiles being not more that 2½ inches thick; but solid firebrick pillars, 15 to 20 inches thick, separate the ovens from each other, and serve as a storage reservoir for the heat, as well as for supporting the roof. This method of storing the heat renders it unnecessary to use heated air for burning the gases. The side wall flues are usually three in number, but in the latest patterns they are four flues high. The coal is charged at the top through three hoppers, and the gases pass away through an opening, also at the top, to the hydraulic main. This is a large iron

pipe extending the whole length of the block of ovens. The condensers are vertical cylinders filled with tubes through which water circulates, and the gases are thus cooled, and deposit tar and ammonia liquors. From these the gases pass to the exhausters, and thence to the washers, where the remaining ammonia compounds are removed. One portion of the gas is generally used for heating purposes, and the other portion is returned to the inside flues

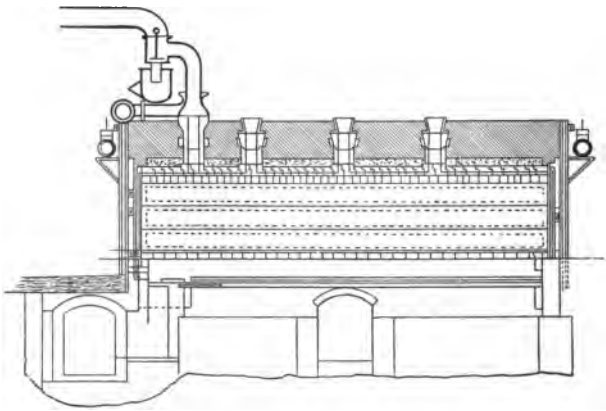


FIG. 13.

of the ovens, where it is burned to heat the ovens. The waste gas is then utilised for heating boilers. The general arrangement of the oven is seen in Fig. 13, which is a longitudinal section.

Otto-Hoffman Coke Oven.—The general shape of this oven is similar to that of the Carvé, but the method of heating is based on the regenerative system of Siemens. The internal flues are vertical instead of being horizontal, and the hot waste gases pass from the flues to the regenerative chambers, giving up their heat to the checker work. Gas from the main is introduced through a pipe into one side of

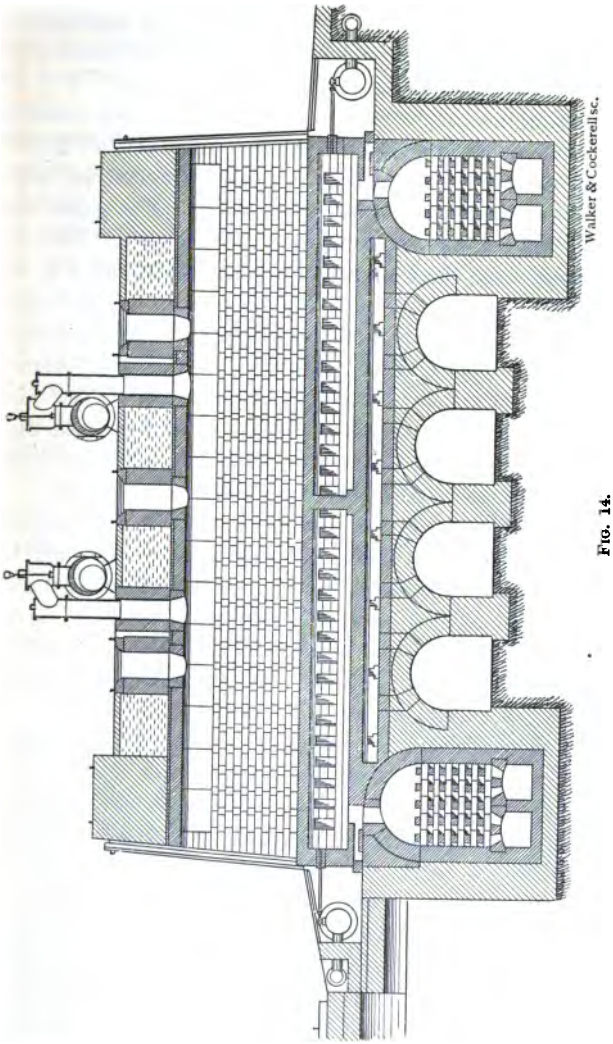


FIG. 14.

the oven flues, and air forced through the hot regenerators by means of a fan. After combustion the flame passes along the bottom chamber at a temperature of 1200° C., into the vertical flues in one wall, uniting again in the top chamber, and from thence down the corresponding vertical flues in the other wall before passing into the regenerators, where the heat is absorbed as described above. The gases next pass to the boilers before entering the chimney. The coal is charged from the top, and the gases drawn off for condensation as in the Carvé and similar ovens. The by-products of such ovens are therefore gas, tar, and ammonia compounds. The cost of a block of 60 of these ovens is £15,000, and with condensing plant £36,000. The yield of coke in these ovens is 74 to 75 per cent. of the coal used, while the yield of the beehive oven is 65 to 68 per cent. The oven is represented in vertical section in Fig. 14.

Composition of Gases.—The composition of the gases liberated from coke ovens during coking varies with the time and mode of coking. The mean of some experiments by Ebelman from a beehive oven gave 10·93 of carbon dioxide, 3·42 of carbonic oxide, 1·17 of marsh gas, 3·68 of hydrogen, and 80·80 per cent. of nitrogen, the first and last being non-combustible. The waste gases of coke ovens have been utilised for heating the ovens themselves, heating boilers, and for the recovery of tar, ammonia, etc.

Desulphurisation of Coal.—Sulphur exists in coal in two ways—firstly, in greater proportion as pyrites; secondly, in sulphate of lime. During coking half the sulphur is driven off from the pyrites, but the whole of that in the sulphate of lime is retained. It is therefore a disadvantage to have sulphate of lime in coal to be used for making blast furnace coke, but a great advantage if the coal has to be burned in an open grate or in a separate fireplace, since the sulphur is retained in the ash and none of it passes into

the gases. Coal is often crushed and washed in order to remove pyrites. Sulphur then is removed partially from coal in two ways (1) by washing, (2) during the coking process.

Gaseous Fuel.—By the use of gaseous fuel it is possible to utilise common varieties of solid fuel and waste products for its production, and also to obtain higher temperatures than ordinarily prevail when burning solid fuel directly on a grate; gaseous fuel leaves no cinder or ash: a higher calorific power may be obtained on account of the smaller quantity of air required for combustion, and therefore less inert nitrogen is present to absorb heat. In burning coal or carbonaceous matter in a limited supply of air, or by causing air to pass through a thick layer of incandescent fuel, carbonic oxide is largely produced, because any carbon dioxide is decomposed by the highly heated carbon. The following is a typical composition of producer gas: 33 of carbonic oxide, CO; 2 of carbon dioxide, CO_2; 2 of hydrogen, H; $3\frac{1}{2}$ of marsh gas, CH_4, and $59\frac{1}{2}$ per cent. of nitrogen, N. If the temperature be allowed to rise too high through too much air being admitted, then more CO_2 will be produced and less of combustible gases.

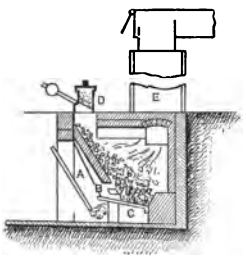


FIG. 15.

Siemens' Gas Producer is a nearly rectangular chamber lined with fire-brick (Fig. 15), 6 feet wide, 6 feet deep, and 3 feet from front to back. The side A is formed of iron plates lined with fire-bricks, having a step grate B and wrought-iron bars C. The fuel is charged through the hopper D. The gas passes up the pipe E, which is cased with iron, and thence into a horizontal wrought-iron pipe, which conveys it to the regenerator. The combustible por-

tion of the gas consists chiefly of carbonic oxide (CO) termed "air" gas. When a jet of steam is introduced the gas liberated contains more hydrogen.

The Wilson Gas Producer (Fig. 16) is used in connection with two steam jets, working under a slight pressure, and fine slack can be used. It is a closed circular iron vessel A, lined with fire-brick, and having a solid hearth, so that

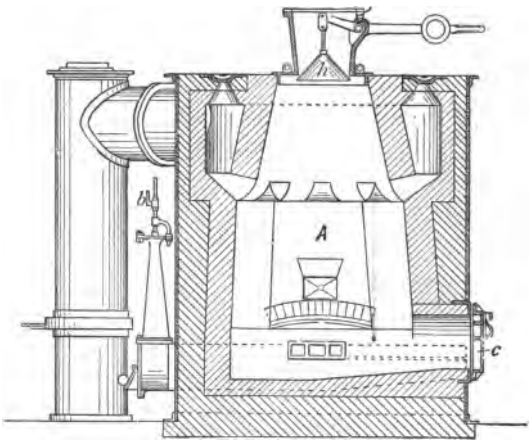


FIG. 16.

forced air is required. This is effected by means of steam jets *b* directed into a conical trumpet-mouthed nozzle, and by its injection drags air into the pipe. The blast enters the inside of the producer through a T-shaped distributor, and consists of 5 to 10 parts of steam to 100 parts of air. The producer is about 8 feet in diameter, and burns 4 cwt. of coal per hour.

A modification of the Siemens' gas producer (Fig. 17) is described by Lencauchez as used at Anzin.[1] The

[1] *Journ. Iron and Steel Institute*, No. II., 1894.

producer is blown with a fan or injector. The following is an analysis of the gas produced:

Hydrogen,	6·88
Carbonic oxide,	25·84
Olefiant gas,	3·85
Marsh gas,	0·57
Carbon dioxide,	0·45
Nitrogen,	62·41

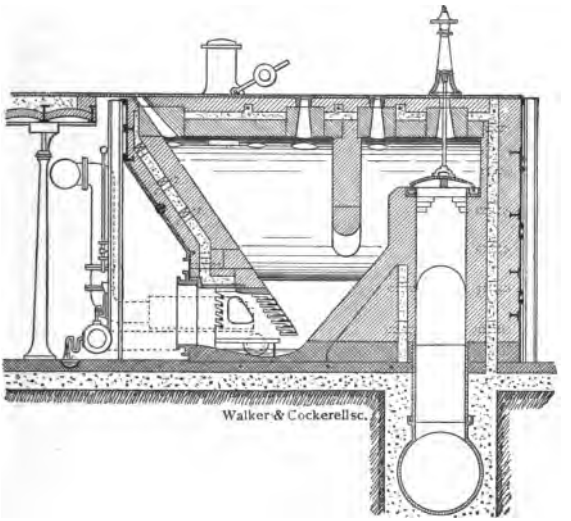


FIG. 17.

The calorific value is 1362 calories per cubic metre. In the case of pyritic fuels the gas is washed in water, so as to remove the sulphurous acid and some of the carbon dioxide. The grates have closed ashpits supplied with water. On this account a considerable amount of steam is decomposed, and this reduces the amount of nitrogen in the gas.

Water-gas.—When steam is passed over incandescent coke or carbon the water is decomposed, and a mixture of

carbonic oxide and hydrogen is produced; this is termed water-gas. A large cylinder of iron is lined with fire-brick, and at the top is a kind of cup and cone arrangement for charging the coke, which is the combustible used. Supposing the chamber to be hot from a previous operation, a forced blast of air is introduced until the whole mass is in an incandescent state. The blast is then stopped, the charging hole being closed, and a current of steam is blown through the red-hot coke. The oxygen unites with the carbon, forming carbonic oxide, and the hydrogen is liberated. Water-gas therefore consists of equal volumes of carbonic oxide and hydrogen, as shown in the equation: $H_2O + C = CO + H_2$, or a ratio of 14 : 1 by weight. Such a gas is very valuable for purposes where a very high local temperature is required. Now, as mentioned above, some of the carbon is first burnt by air and forms ordinary producer gas, and as air contains a large proportion of nitrogen, this product is a mixture of gases of which 60 per cent. is inert nitrogen. The producer gas thus obtained has burnt 75 per cent. of the carbon, so that only 25 per cent. of the total carbon is burnt to the condition of water-gas. If the whole of the carbon could be burnt direct by steam, then water-gas would be very economical: 75 parts of carbon will yield 551·19 parts of producer gas, of which 175 parts are carbonic oxide; 25 parts of carbon will yield 62·5 parts of water-gas, of which 4·16 is hydrogen, and 58·34 is carbonic oxide. The amount of heat produced by the combustion of the above producer gas is nearly double that obtained by the combustion of the above water-gas. For ordinary heating purposes at very moderate temperatures the direct use of solid fuel is preferable to that of gaseous fuel, but where very high temperatures are required gaseous fuel is to be preferred, because with it the principle of regeneration can be applied, and a less volume of air is

required for complete combustion, and therefore less heat is wasted in the chimney gases. The addition of steam to an ordinary gas producer, such as Wilson's, causes a richer gas to be produced, due to about 10 per cent. of free hydrogen, which gives such gas a higher calorific power. Now water-gas with its comparatively high calorific power possesses only about half the heating power of coal gas, but it burns with a smokeless flame of such small size as to give a local temperature much higher than that of a coal-gas flame. Unfortunately water-gas is five or six times as poisonous as coal-gas. It is also scentless, so that some odorous gas has to be mixed with it to render its presence known. For fuller information see *Journal of Iron and Steel Institute*, Vol. II., 1889.

Mond Gas.—This is producer gas obtained from a special producer introduced by Dr. Ludwig Mond in 1889. Its object is to obtain a gas for heating purposes as well as to recover sulphate of ammonia. When fuel is gasified in the ordinary producer the products of distillation, including tar, leave the fuel first, and the fixed carbon is converted into carbonic oxide. This raises the temperature to such a degree that the ammonia compounds are decomposed, the volatile products distilled and the initial heat in the gas is lost to a great extent. Dr. Mond aims at utilising this heat by transferring the sensible heat to the steam and gas by means of a recuperative method (Fig. 18),[1] thus enabling more steam to be used than is usually the case and preventing the decomposition of the ammonia. The amount of nitrogen in fuels averages about 1·4 per cent., and by using superheated air and 2½ tons of steam for every ton of fuel, about 70 per cent. of this nitrogen is recovered as sulphate of ammonia, thus producing nearly 100 lbs. of this sulphate from one ton of fuel. About one-third of the

[1] *Journ. Iron and Steel Institute*, No. I., 1896.

steam is decomposed, leaving two-thirds in the gases. These gases amount to 160,000 cubic feet per ton of fuel. They are passed through a series of pipes surrounded by an annular space, through which the steam and air admitted to the producer passes in the opposite direction, thus taking up the heat from the hot gases. The producer gas is then led through a rectangular chamber filled with water, which

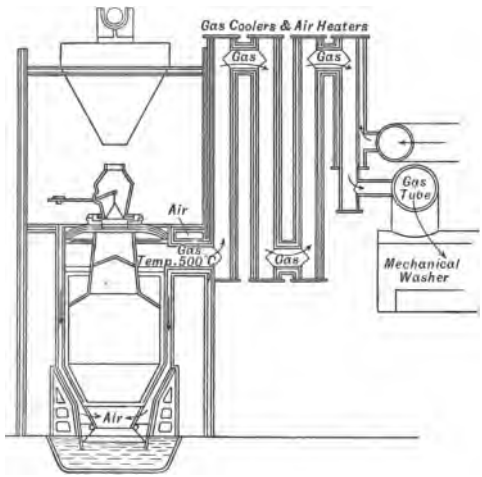


FIG. 18.

is thrown up in a fine spray by revolving beaters, and this washes the dust and soot out of the gases. The gas then passes to a scrubber in which the ammonia contained in the gases is absorbed by dilute sulphuric acid. The gas then passes to a second scrubber where the steam is condensed by cold water, and from thence it passes to the mains for use.

The gas producer is cylindrical in shape, tapering at the bottom, 10 feet in diameter in the cylindrical part and 21 feet high. The bottom ends in a conical grate with a round opening at the centre, through which the ashes fall into the

water lute. The upper portion has a cone and hopper for charging, and underneath the cone is a bell-shaped casting kept partially filled with fuel. The casing of the producer is made of double iron plates, between which air and steam are blown in and circulate round the producer. The gases are thus superheated and then pass to the conical grate. The producer is kept filled with fuel up to the bell-funnel. The gas passes away by a pipe to a series of iron tubes, and thence to the washer. The quantity of fuel gasified by one producer in 24 hours is about 20 tons. The composition of the dry gas is:

Carbon dioxide,	17
Carbonic oxide,	11
Hydrocarbons,	2·2
Hydrogen,	27
Nitrogen,	42·8
	100

Mr. Darby gives the following analyses by volume of various producer gases:

	Mond gas.	Brymbo.	Dowlais.	Bolchow, Vaughan & Co.
Carbon dioxide,	17·1	7·63	7	7·0
Carbonic oxide,	11·0	21·73	22	21·5
Ethylene,	0·4	1·06	—	—
Methane,	1·8	3·05	1	1·5
Hydrogen,	27·2	12·60	9	10·0
Nitrogen,	42·5	53·80	61	60·0

	Scotch blast furnace gas.	Steel Company of Scotland.	Siemens' closed steam blown.	Wilson gas.
Carbon dioxide,	8·61	8	5·2	5·25
Carbonic oxide,	28·06	22	24·4	23·60
Methane,	4·37	4	2·4	3·05
Hydrogen,	5·45	15	8·6	10·55
Nitrogen,	53·38	51	59·4	57·55
	99·87	100	100·00	100·00

CHAPTER IV.

ORES OF IRON.

Native Iron.—Iron in the metallic state is of very rare occurrence, and this may be accounted for by its great affinity for oxygen and other non-metals. Large masses of iron, known as meteorites, are occasionally found in different parts of the world; they are easily distinguished from the masses of terrestrial origin, as they invariably contain nickel (which very rarely occurs in ordinary iron ores), and the metal is usually found in a mass containing crystals. The mass is nearly always covered on the surface with a thin coating of oxide, which protects the metal from oxidation. Berzelius gives the analysis of a mass from Siberia weighing 1600 lbs. and of one from Bohemia weighing 103 lbs. Stromeyer analysed an enormous mass found near Treves which weighed 3300 lbs.

Iron occurs in a great variety of minerals, but the oxides and carbonates are almost the only forms utilised by the smelter.

Magnetite or Magnetic Iron Ore.—When pure it contains 72·41 per cent. of iron, and is represented by the formula Fe_3O_4. It is sometimes crystalline, but more generally massive. It is black or dark brown in colour, brittle, magnetic, and leaves a black streak when drawn

across a plate of unglazed porcelain; it has a specific gravity of about 5·2. It occurs in granite, gneiss, clay-

ANALYSES OF METEORITES.

Locality.	Bohemia.	Siberia.	Treves.
Analyst.	Berzelius.		Stromeyer.
Iron,	93·78	88·04	81·8
Nickel,	3·81	10·73	11·9
Cobalt,	0·21	0·46	1·0
Copper,	—	0·07	—
Manganese,	—	0·13	0·2
Magnesium,	—	0·05	—
Carbon,	—	0·04	—
Sulphur,	—	—	5·1
Insoluble matter,	2·20	0·48	—
	100·00	100·00	100·0

slate, hornblende, chlorite, and occasionally in limestone. Nearly all the Swedish iron is obtained from this class of

ANALYSES OF MAGNETITE.

	I.	II.	III.	IV.	V.
Silica,	5·95	13·20	1·00	—	2·74
Alumina,	1·05	—	3·60	—	1·23
Lime,	2·40	1·21	0·56	—	1·51
Magnesia,	2·50	0·80	1·52	—	—
Magnetic oxide of iron,	87·80	84·30	79·50	95·64	89·66
Phosphoric acid,	0·09	0·03	0·57	0·07	0·37
Manganese oxide,	—	0·24	0·56	—	1·92
Pyrites,	—	—	0·04	0·09	0·02
Water,	—	—	3·20	—	—
Insoluble residue,	—	—	9·40	3·97	2·50

ore, which also occurs in great abundance in the island of Elba, and in the United States of America.

No. I. is from Lapland. No. II. is from Sweden. No. III. is from Devonshire. No. IV. is from Canada, and No.

V. is from the Urals. Magnetic ores when massive generally contain more of the peroxide than is required for the formula Fe_3O_4. They are confined chiefly to the older crystalline rocks in Sweden and North America. The texture of massive magnetite varies with the containing rock, the most compact being found in talcose schist, and more granular and crystalline varieties in hornblende, gneiss, and crystalline limestone. The Canadian magnetite is found in the oldest formations, and usually of high quality. The largest deposits in Europe are said to be in Lapland, where several of the beds are 100 to 200 feet thick, and iron pyrites seem to be absent. Phosphorus is also very low. In the more southern parts of Sweden the ores of Dannemora are of the purest kind and most celebrated. In England magnetite is comparatively rare.

Franklinite.—This ore is similar in colour to magnetite but less magnetic, occurring in crystals and massive. It gives a dark reddish-brown streak, and has a specific gravity of about 5·1. It consists of ferrous and ferric oxides, manganous and manganic oxides, and oxide of zinc. It is chiefly found in New Jersey, and is used as a source of zinc and spiegel-eisen.

Ilmenite.—This is an ore of iron containing titanium. It is a dead-black mineral, generally found massive, sometimes crystalline, as well as in plates and scales. It has a hardness of about 6, and a specific gravity of 4·5 to 5. The composition varies, but a general formula may be taken as $FeO \cdot TiO_2 + Fe_2O_3$. It occurs in most crystalline rocks, and haematite and magnetite often contain small portions of this mineral. By the disintegration of such rocks, sands containing ilmenite are formed; and on account of its high specific gravity it is easily separated. It occurs abundantly in Norway and Canada, and also in New Zealand, the United States, and India. This ore is difficult to reduce

in the blast furnace. It has been used for lining revolving puddling and other furnaces on account of its refractory character.

Chrome Iron Ore, also termed Chromite. The amount of chromium varies, so that no definite composition can be given. It often contains magnesia and alumina. It may be looked upon as ($FeO \cdot Cr_2O_3$). It is sometimes crystalline, but generally granular or compact. Its colour is iron-black or brownish-black. It gives a brown streak, has a hardness of about 5·5, and a specific gravity of about 4·5. It occurs chiefly in Canada, Germany, Sweden, Norway, and India. It is somewhat infusible, and being neutral in character, is used for furnace linings.

Haematite.—Composition Fe_2O_3, containing 70 per cent. of iron when pure. It exists in crystals, in fibrous, columnar, kidney-shaped, granular, and compact forms. Its colour varies from dark iron-grey in the crystallised, to deep-red in the compact varieties. Its specific gravity is as high as 5·3 when in crystals, and as low as 4·2 in earthy varieties. Special names are given to different forms, thus: Specular ore, as in the brilliant crystalline species of Elba and Brazil. Micaceous ore, as in the scaly varieties of South Devon. Kidney ore, as that from Cumberland. Red ochre is a compact earthy variety, often containing clay. Puddlers' ore is a compact, unctuous form from Cleveland, and used for lining puddling furnaces. Spanish or Bilbao ore is a siliceous haematite containing manganese, and noted for its purity, hence its use in the open-hearth steel process.

Haematite is often associated with the hydrated oxide, especially in the newer and secondary rocks, but in the older formations water is generally absent. The Devonian rocks of England and Germany contain much haematite. The most important deposits in this country are at Ulver-

stone in Lancashire and Whitehaven in Cumberland. It is for the most part of a dull compact character, but forming kidney-shaped crystalline aggregates in the cavities where quartz, aragonite and specular ore are present. In the Ulverstone district the ore is usually found filling cavities in the limestone. A greasy micaceous variety is also found and used for lining puddling furnaces. In both districts brown haematite is absent, and iron pyrites and phosphate of lime only occur in minute traces. These ores, owing to their freedom from phosphorus and sulphur, are largely used for making pig iron for the Bessemer process. Red haematite is found in Flintshire, South Wales, North Staffordshire, Cornwall, and Devon. The following are some analyses of haematite ores:

	I.	II.	III.	IV.
Ferric oxide, - -	93·53	83·24	70·00	72·36
Manganese oxide, -	0·23	0·28	0·95	—
Alumina, - -	0·63	0·70	1·12	3·94
Lime, - - -	0·05	0·85	4·64	1·75
Magnesia, - -	—	0·09	0·59	0·86
Phosphoric acid, -	—	0·03	0·03	—
Silica, - - -	4·90	12·46	7·50	10·20
Sulphur, - -	0·01	—	—	—
Water, - - -	0·56	2·28	13·12	10·76
Carbon dioxide, -	—	—	2·00	—

No. I. is a typical ore from Ulverstone district. No. II. is from Cumberland. No. III. from Spain, and No. IV. from New South Wales.

Brown Haematite.—The proportion of water varies in the different varieties, and is usually from 10 to 15 per cent. It is distinguished generally by a brown colour, but has sometimes a bright yellow colour, and gives a corresponding streak. It may be typically represented by the formula ($2Fe_2O_3 . 3H_2O$). It occurs in irregular, compact masses in

the carboniferous limestone and lower coal measures of the Forest of Dean, Gloucestershire, and in Glamorganshire. In the Lias, Oolites, and Lower Greensands of Northamptonshire, Lincolnshire, Buckinghamshire, and Oxfordshire, a less pure variety is found more or less mixed with sand. The chief minerals consisting of hydrated ferric oxide are:

Goethite ($Fe_2O_3 . H_2O$).—This mineral may be crystalline, scaly, or fibrous, with a colour varying from rust-yellow to black. It contains about 63 per cent. of iron when pure, and has a specific gravity of 5·5.

Limonite ($2Fe_2O_3 . 3H_2O$).—This mineral is found in mamillated or stalactitic forms, often with a radiating fibrous structure. It is dull in lustre. Some varieties are earthy in character. The finer deposits are used as pigments.

Bog Ore is a loose, porous, earthy variety, found in low lying, or swampy ground, often impregnating or enclosing fragments of wood, leaves, mosses, etc.

Lake Ore is a variety which occurs in granular concretionary masses, dredged during the winter months from certain lakes in the north of Europe.

ANALYSES OF HYDRATED OXIDES OF IRON.

	I.	II.	III.	IV.	V.
Ferric oxide,	90·05	75·20	52·86	64·50	61·00
Manganese oxide,	0·08	0·30	0·51	0·60	—
Alumina,	0·14	—	7·39	3·16	5·10
Lime,	0·06	—	7·46	2·50	4·62
Magnesia,	0·20	—	0·68	—	1·48
Silica,	0·92	5·40	13·16	12·89	12·64
Phosphoric acid,	0·09	1·81	1·26	1·30	—
Water,	8·22	17·25	11·37	15·05	14·86
Carbonic acid,	—	—	5·32	—	—

No. I. is from the Forest of Dean. No. II. is a sample of bog ore from Canada. No. III. is from the Oolitic limestone.

No. IV. is a rich Northampton ore. No. V. is from New South Wales. Most of these ores contain traces of sulphur.

Siderite, Chalybite or Spathic Iron Ore.—This is a carbonate of iron $FeCO_3$. This class is the chief source of British iron. Manganese is often present in spathic ore, in some cases to the extent of 50 per cent. The pig-iron obtained from ores rich in manganese is termed spiegel-eisen. Spathic iron ore or chalybite when pure contains 48·25 per cent. of iron. It is sometimes found in crystals and crystallises in the hexagonal system, but generally it is massive, cleavable and granular. It has a pale yellow or buff colour, sometimes brownish-black or brownish-red with a pearly lustre. It gives a white streak, has a hardness of about 4, and a specific gravity of 3·8. In Styria some varieties are white and very free from phosphorus. Clay ironstone is an impure variety of chalybite, and forms the most abundant British ore of iron. It contains about 15 per cent. of clayey matter. It varies in colour with the nature of the gangue. Enormous masses of spathic ores occur in central Europe, in Scandinavia, and North America. The principal deposits in this country are in Durham, Cornwall, Devon, and Somerset. Also in South Wales, Staffordshire, and West Yorkshire large deposits occur. In Staffordshire a number of varieties occur, termed brooch-stone, pudding-stone, lamb-stone, white-stone, gubbin, etc. Cleveland ironstone, of the North Riding of Yorkshire, is an impure variety of clay ironstone, and forms immense beds of fairly uniform composition. The two chief beds are termed the "pecten" and "avicula" seams, from their characteristic fossils. The main bed has its greatest thickness at Eston.

Blackband.—This is a variety of clay ironstone in which the ore is interstratified with bituminous matter. It occurs somewhat abundantly in the Western Coal-fields of Scot-

land, in Lanark, in North Staffordshire and in South Wales. A good variety of this ore occurs in North Staffordshire, and is employed as a fettling in puddling furnaces under the name of "pottery mine." Owing to the large amount of bituminous matter contained in blackband ironstone it can often be calcined without any additional fuel.

The following analyses will show the composition of spathic and clay ironstones:

	I.	II.	III.	IV.	V.
Ferrous oxide,	50·00	50·60	47·50	39·92	40·27
Ferric oxide,	—	—	—	3·20	2·72
Manganese oxide,	1·09	5·50	0·90	1·70	—
Alumina,	—	3·50	4·80	9·80	—
Lime,	3·47	0·90	1·90	3·60	0·44
Magnesia,	3·20	0·80	1·90	4·40	0·42
Silica,	5·10	—	9·40	8·30	—
Carbon dioxide,	37·10	38·50	31·60	21·89	25·41
Phosphoric acid,	—	0·04	0·05	1·86	1·86
Sulphur,	0·04	—	—	0·11	0·06
Water,	—	—	1·81	4·90	0·97
Clay,	—	—	—	—	10·60
Organic matter,	—	—	—	—	17·38

No. I. is from Durham. No. II. is from Styria. No. III. is from Staffordshire. No. IV. is from Cleveland. No. V. is Scotch blackband.

The table on page 62 shows at a glance the typical composition of different varieties of iron ores.

Iron Pyrites.—This mineral is very abundant in nature, and is only used as a source of iron after the sulphur has been burnt off for the manufacture of sulphuric acid, when the resulting oxide is known as blue-billy. Some varieties are bronze-yellow, others are nearly white in appearance. Several different forms occur. Pyrites has a pale brass-yellow colour, with a greenish-black streak. It is brittle, hard, and strikes fire with steel. It has a hard-

Name.	Magnetic Iron Ore.	Red Hæmatite.	Brown Iron Ore.	Spathic Ore.	Clay Ironstone.		Cleveland Ore.
Locality.	Danne-mora.	Ulverstone.	Dean Forest.	Brendon, Somerset-shire.	Black-band Lowmoor.	Dudley.	Eston.
Ferric oxide (Fe_2O_3),	27·55	93·23	90·05	0·81	1·45	0·40	3·60
Ferrous oxide (FeO),	58·03	—	—	43·04	36·14	45·86	39·92
Manganese oxide (MnO),	0·10	0·23	0·08	12·64	1·38	0·96	0·95
Alumina (Al_2O_3),	0·29	0·63	0·14	0·01	6·74	5·56	7·86
Lime (CaO),	0·38	0·05	0·06	0·28	2·70	1·37	7·44
Magnesia (MgO),	0·61	—	0·20	3·63	2·17	1·85	3·82
Potash (K_2O),	—	—	—	—	0·65	—	0·27
Silica (SiO_2),	12·54	4·90	0·92	0·07	17·37	10·68	8·76
Carbon dioxide (CO_2),	0·12	—	—	38·86	26·57	31·02	22·85
Phosphorus pentoxide (P_2O_5),	—	—	0·09	—	0·34	0·21	1·86
Sulphur trioxide (SO_3),	—	0·09	—	—	—	—	—
Sulphur,	0·04	—	—	—	—	—	0·11
Iron pyrites (FeS_2),	—	0·03	—	—	0·10	0·10	—
Water,	0·11	0·56	8·22	0·18	1·77	1·08	2·56
Organic matter,	—	—	—	—	2·40	0·90	—

ness of 6·5, a specific gravity of about 4·5, and crystallises in the cubic system. Marcasite is another form of FeS_2. It is of a paler colour than pyrites, and crystallises in the rhombic system. It decomposes more readily, and is used for the same purposes as pyrites.

Pyrrotine.—This is a magnetic variety of pyrites. It crystallises in the hexagonal system: has a reddish-brown or bronze colour, readily tarnishes in air. It gives a dark greyish-black streak. It is softer than pyrites, having a hardness of about 4·0, and a specific gravity of 4·5. Its chemical formula is Fe_6S_7.

British Iron Ores.—Red haematite is obtained from Lancashire and Cumberland. Red and brown haematite from Cornwall and Devon. Brown haematite from the shires of Gloucester, Wilts, Oxford, Northampton, Leicester, Lincoln, and North Stafford; from Ireland, and the Isle of Man. Clay ironstone and black band from Staffordshire, Yorkshire, Wales, and Scotland. Spathic iron ore from Somersetshire, and spathic and brown haematite from Durham and Northumberland. Of the above ores, the rich and pure haematites of Lancashire and Cumberland are valuable for the iron used in the acid Bessemer process, and for the cementing process of making malleable iron, and as fettling for puddling furnaces.

The ores most prized for steel-making are those most free from phosphorus, the limit of phosphorus in pig-iron for steel-making, other than by basic processes, is generally taken as 0·04 per cent. Turner[1] makes the following classification:

Non-phosphoric—	Phosphorus per cent. in pig iron.
Swedish magnetites,	0·00 to 0·06
Cumberland haematite,	0·04 to 0·06
Spanish ore,	0·04 to 0·06
Forest of Dean,	0·07

[1] *Metallurgy of Iron*, p, 61.

Phosphoric—	Phosphorus per cent. in pig iron.
Purple ore (blue billy),	0·10
Lake Superior,	0·10
South Staffordshire,	0·40 to 0·60
Leicestershire,	0·60
Blackband,	0·60
North Staffordshire,	0·80 to 1·00
Rhenish brown haematite,	about 1·00
Northampton brown haematite,	1·00 to 1·50
Cleveland ironstone,	1·10 to 1·75
Lake and bog ores,	variable, about 2·00

Genesis of Ore Deposits.—Iron ores occur in beds, veins, and masses. Ores generally may have been concentrated with or without a change in the state of aggregation. In the former case the passage into the solid state is from the condition of vapour, or from the liquid condition, or from a state of solution. Hence we may get sublimation deposits, in which the solidification of the vapours may take place simultaneously with that of a solidifying magma. Or the metallic mineral may solidify as a deposit. Or the mineral may be deposited from a solution by precipitation along with other sediment, thus forming seams and beds. Or it may be precipitated on the muddy floor of a lake, in the form of nodules of clay ironstone. Or we may have separation deposits, formed by chemical concentration, a more soluble constituent being carried away, leaving the iron compound behind. Winchell gives the following classification:

A. Mechanical. I. By fall of meteorites. II. By eruption in dykes or basaltic flow. III. By abrasion and transport to other situations.

B. Chemical. Change in the kind or quantity of iron already present in the rock; such as the alteration of ferric oxide into ferrous carbonate, removal of ore by chemical solution and subsequent precipitation, or by saturation of porous strata, or deposition by springs.

Geological Distribution of Iron Ores.—Ironstone mining in Cornwall is of recent date. The principal mines contain brown haematite, occurring in irregular beds, lying between the older rocks. In Devonshire haematite occurs in irregular deposits, interbedded with limestone. A valuable deposit occurs near Brixham, and lies between the mountain limestone and the Whitehead limestone. The ferric oxide varies from 77 to 92 per cent., and the phosphorus is very low.

The coal measures of the Forest of Dean contain iron ore below the Millstone grit in the upper part of the Carboniferous limestone. The ore fills up large cavities in the limestone, which are connected by strings or leaders. The brush ore is a haematite often yielding 80 per cent. of oxide of iron, together with some kidney ore. Another ore consists of finely powdered haematite associated with limonite. Large irregular nodules of ore are common. Some distance above the larger and purer deposits are veins, known as "Sandstone veins in the Millstone grit."

In Lancashire and Cumberland are large deposits of haematite in the carboniferous limestone, somewhat similar to those of the Forest of Dean. These deposits are irregular, and fill up cracks, joints, cavities and soft beds in the upper limestone. Botryoidal forms occur in cavities. These ores yield a pure haematite practically free from phosphorus, although some inferior varieties are also found. The older rocks in the district are largely impregnated with iron. Similar deposits also occur in the Silurian rocks in Cumberland.

The iron ores of the coal-measures occur in most of the series, from the upper to the lower, although the lower are the most productive. The blackband of Staffordshire, Lancashire, and Scotland, occurs in the upper series. The clay ironstone of Staffordshire, Warwickshire, and North Wales lies under the coal, or between the main and lower

yard coals in the lower series. The beds of South Wales and South Staffordshire lie in the lowest series. There are also associated with the coal seams bands of iron pyrites.

In the Jurassic formation we get beds of iron ore in Yorkshire, Northamptonshire, and Leicestershire. The main Cleveland seam is in the Lower Lias, and the top seam in the Lower Oolite. In Lincolnshire, seams occur in the Lower Oolite and the Lower Lias. The Northamptonshire beds are in the Lower Oolite.

Deposits of iron ore may be summarised geologically as existing in formations of all ages, the first and oldest being found in rocks from the Cambrian to the Carboniferous, the second in the Coal-measures, and the third in strata ranging from the Permian to the Recent formations. Magnetites are found in the pre-Cambrian rocks and are therefore the oldest and those that have been most subjected to high temperatures and violent disturbances. Magnetites may therefore be the source of all other ores of iron. Next in age seem to be haematites, of which the hydrated oxides are the newer. Carbonate ores may belong to the same category as haematites as regards age, or they may have been derived from the decomposition and changes of haematites and magnetites, or, the whole may have been derived from the decomposition of ferrous carbonate in solution. Probably many of these actions and reactions have taken place over and over again. Iron pyrites also occur in the oldest crystalline and metamorphic rocks, and by their oxidation may produce the oxides, and these in the presence of water and carbon dioxide under certain conditions would form the carbonate. In America the magnetites and haematites chiefly occur in the older rocks, red fossil ore in the Silurian, and the carbonates in the Carboniferous formation. In central Europe iron ores occur much the same as in this country.

CHAPTER V.

CHEMICAL RELATIONS OF IRON.

PURE iron is not a commercial article except as a medicine, but it may be obtained in several ways. 1°. By reducing pure ferric oxide in a porcelain tube by means of a current of hydrogen gas at 700° C.; the iron is obtained in the form of a dark powder, which when somewhat heated, fires spontaneously in contact with air, forming Fe_2O_3 again. When the reduction is effected at a much higher temperature, a spongy mass of a silvery-grey colour is obtained. 2°. By strongly heating the purest variety of iron wire with a little pure oxide of iron, covering the mixture with powdered glass free from lead, and exposing the whole to a high temperature in a covered clay crucible. The small portion of carbon present in the wire is removed in reducing the oxide, while the other impurities pass into the slag. 3°. By electrolytic decomposition of a solution of pure ferrous chloride or sulphate, a mass of silvery-white, soft, malleable iron is obtained, which, after annealing, has a specific gravity of 7·81.

Iron may be exposed to dry air for an indefinite period without alteration, but in the presence of moisture a layer of rust (Fe_2O_3, H_2O) is formed. The oxidation is accelerated by the presence of carbon dioxide, which is always present in the air, a carbonate of iron being formed.

This rapidly absorbs a further portion of water and oxygen from the air, and in this way the rusting is slowly conveyed to the centre of the mass of iron. The layer of oxide or carbonate is electro-negative with regard to iron, so that an electrical action is set up, causing decomposition of the water. This electrical condition still further augments the liability of iron to rust.

When iron is strongly heated in contact with air or oxygen, its surface becomes rapidly coated with a scale of black oxide Fe_3O_4, which peels off when the iron is struck with a hammer.

Protection of Iron.—Prof. Barff introduced a process for the protection of iron surfaces by forming on them a coating of magnetic oxide. This is effected by heating the articles to redness and passing over them a current of superheated steam. The steam is decomposed by the iron, liberating hydrogen and the oxygen unites with the iron. Subsequent to this, another inventor named Bower obtained a similar result by the use of a limited supply of air, for if too much air is used ferric oxide is formed which is useless for protective purposes. A combination of both methods is now carried on under the title of the Bower-Barff process.

The articles to be coated are placed in a firebrick chamber and there heated by means of producer gas. When the temperature has been sufficiently raised, superheated steam is substituted for producer gas. By this means the surface is converted into the magnetic oxide by the steam in the second part of the process. The temperature employed is 560° C., but the time of heating varies with the size and quantity of the articles as well as with the thickness of the coating desired. Bertrand has patented a process of coating iron by first cleaning in dilute sulphuric acid and then immers-

ing for a few seconds in a bath, consisting of 200 grams of "acid tin salts," 600 grams of copper sulphate and 300 grams of sulphovinic acid in 100 litres of water. The articles should have a yellowish bronze colour and be washed in water containing a little oxalic acid, then dried and heated in an oven. This process is stated to impart a coating of magnetic oxide.

Iron is protected from oxidation by the deposition of different metals on its surface, such as copper, tin, zinc, and nickel.

Copper, to be deposited on iron, must be in solution in potassium cyanide, and the deposition effected by means of an electric current. A thin coating may be imparted by simple immersion in a solution of copper sulphate. If any of the coating wears off, the two metals acting as an electric couple will cause more rapid oxidation.

Nickel is applied as a protective coating to iron. It is deposited by electricity from a neutral solution of ammonia sulphate of nickel. It forms a hard durable coating and is much less oxidisable than iron, but the latter rapidly oxidises if the coating is worn off in places.

Tin is very largely used for coating iron, and special sheets of iron are manufactured for tinning and termed tinplate. The tin is applied by simply dipping the cleansed iron in molten tin, when an adherent coating is obtained.

Zinc is used as a coating on iron, which is then termed galvanised-iron. It is applied like tin by immersing the cleansed iron articles in molten zinc, the surface of which is covered with sal-ammoniac, which acts as a flux. As zinc is dissolved by vegetable acids this metal should not be used for coating cooking utensils.

The use of pigments and varnishes will not be considered here.

Action of Acids on Iron and Steel.—Iron is readily

attacked by hydrochloric—or dilute sulphuric acid, hydrogen gas being evolved and chloride or sulphate of iron formed. If concentrated sulphuric acid be employed, the metal is oxidised at the expense of the acid, and sulphur dioxide is evolved. If a clean strip of iron be immersed in fuming nitric acid the iron is not attacked, and is said to remain passive; if the temperature be raised, or the iron be touched with a copper wire, dissolution immediately begins. Ordinary nitric acid attacks iron vigorously, especially if slightly diluted, nitrate of iron being formed. Iron may be rendered passive to nitric acid by removing it from the liquid, exposing it to the atmosphere, and then re-immersing in the acid.

Iron often contains impurities, such as carbon, silicon, phosphorus, etc., and when such iron is dissolved in sulphuric or hydrochloric acid, the evolved hydrogen unites with the combined carbon, sulphur, and phosphorus to form gases which have a disagreeable odour. When white cast iron is dissolved this action is intensified. With grey cast iron an insoluble residue is left, containing graphite and silica. White cast iron resists the action of acids more than grey cast iron, and is employed for vessels used in parting gold from silver by the sulphuric acid process.

Ledebur has shown that the resistance of iron to the action of very dilute sulphuric acid increases with the increase in carbon. The acid used had a density of 1·05, the metals tested were in the form of cubes, and the acid was allowed to act for 65 days, with the following percentage of loss in each case:

Wrought iron,	88·60
Unhardened tool steel,	66·50
Refined charcoal pig,	37·70
Grey coke pig,	27·60
White pig,	19·70
Spiegel-eisen,	14·15

Andrews has also shown that iron with much carbon is less readily attacked by nitric acid than pure iron. As regards corrosion of iron in different kinds of water, wrought iron and mild steel seem about equal, but wrought iron is more readily attacked by acidulated water. In locomotive boilers steel seems less corrodible than iron, but in marine boilers the difference is less marked. The presence of manganese seems to hasten corrosion, and that of much silicon to prevent oxidation. Cast iron with the skin left on is not easily corroded, but the same with the skin taken off is more quickly oxidised.

Oxides of Iron.—There are three oxides of iron of metallurgical importance, ferrous oxide, FeO ; ferric oxide, Fe_2O_3 ; and tetroxide of iron Fe_3O_4, which may be considered a combination of the two former. Ferrous oxide is a very unstable oxide, readily passing into a higher oxide in the presence of oxygen. It readily unites with water forming ferrous hydrate, which is produced by precipitation from a ferrous salt by means of potash or soda, but this soon changes from white to brown owing to the absorption of oxygen. The anhydrous oxide may be prepared by passing equal volumes of carbon dioxide and carbonic oxide over red-hot ferric oxide, producing a black amorphous, unstable body. It may also be obtained by igniting ferrous oxalate, but it is then mixed with metallic iron. This oxide is the principal base in all iron slags produced in the refining of iron, having the general formula, xFeO . SiO_2. Ferrous silicate is also formed by the action of silica on ferric oxide, at very high temperatures, especially in the presence of carbon. In combination with carbon dioxide it forms ferrous carbonate, which is the chief source of British iron. In combination with phosphorus pentoxide it forms a phosphate which is of great importance in some iron slags. There are several known combinations of

ferrous and ferric oxides, of which the most basic is that of magnetite and iron scale.

Ferric Oxide.—This oxide occurs largely in nature as haematite, and in the hydrated form as brown haematite. It is prepared artificially by calcining ferrous sulphate, producing a bright red powder, termed rouge, colcothar, and crocus. Pulverulent varieties of this oxide are obtained by calcining other iron salts, such as the nitrate, persulphide, and oxalate. It occurs in nature in a beautifully crystalline state as specular ore, iron glance, etc. At ordinary temperatures ferric oxide is a stable compound, but at a white heat it is converted into the magnetic oxide, with evolution of oxygen, and this explains why magnetic oxide is formed when iron is burnt in oxygen, as well as in welding and forging. For this reason ferric oxide is a powerful oxidising agent. It is reduced by carbon and by carbonic oxide, but the reduction by the carbonic oxide is never complete unless carbon is present. Even comparatively large pieces of haematite may be reduced by carbon, and in this case the carbonic oxide formed penetrates into the porous mass, effecting its reduction. Ferric oxide, like alumina, can act as an acid in combination with a stronger base, such as lime. Iron rust is essentially a hydrated oxide of iron, in which the amount of water is variable, as observed by the different colours of different samples. This water tends to pass away in time, and the residue is practically pure Fe_2O_3.

Hydrated ferric oxide may be produced by precipitation from a solution of a ferric salt by means of ammonia, and having the chemical formulae, Fe_2O_3, $3H_2O$. This oxide forms the base of a large class of minerals, termed brown haematite, limonite, etc., and is the product formed when ferrous oxide is exposed to air and moisture, or when ferrous hydrate is exposed to the action of the air.

Hydrated ferric oxide is slightly soluble in water containing carbonic acid, or any soluble organic salt of ammonia, such as may be produced by the decomposition of vegetable matter. In the latter case the solution is attended with a reduction of the ferric to a proto-salt of the organic acid. It will be seen from these reactions how great and diverse changes can occur in nature, and how diversified the compounds of iron may be.

Magnetic Oxide of Iron (Fe_3O_4).—This oxide is a very stable compound of iron, as may be seen from the fact that it exists in the oldest rocks, those that have been subjected to the most violent changes and metamorphosing agencies. It may be looked upon as a compound of three atoms of iron with four atoms of oxygen, or as a compound of ferrous oxide, FeO, with ferric oxide, Fe_2O_3, in which the ferrous oxide plays the part of a base and the ferric oxide that of an acid. This is borne out by the fact that the FeO is replaced by other basic oxides, such as that of zinc in Franklinite, or that of manganese in many magnetites. Also the ferric oxide is replaced by Cr_2O_3 in chrome iron ore, and possibly by Al_2O_3 in spinels. In nature, magnetic oxide is found crystallised in the cubic system, forming a lustrous black mineral, which may be artificially imitated by passing steam over red-hot iron, when small brilliant black octahedral crystals are formed on the surface of the metal. It is further distinguished from the other oxides of iron by being magnetic, and in nature is often found to be polar, hence the name of magnetic oxide or lodestone. The magnetic properties depend more on molecular condition than on purity of composition, and they are best developed in the compact slaty varieties, which are often very impure.

Iron and Silicon.—The effect of silicon in iron is further discussed in the portion of this book devoted to steel. Silicon is a non-metal, and exists in three different states,

namely, as amorphous silicon which is a dull brown powder insoluble in water. As graphitic silicon which is obtained by heating the amorphous variety in a platinum crucible, when it became denser, harder, and less oxidisable. It has a density of 2·5, and may be heated to whiteness in oxygen without undergoing any change. The other form is the crystalline or adamantine form. It crystallises in the cubic system in the form of rhombic octahedra. Silicon is said to have a melting point below that of iron, or about 1400° C. It combines most readily with iron when its oxide is reduced in the blast furnace. Seeing how difficult it is to get silicon to unite with oxygen in the free state, it is very remarkable that it should so readily unite with iron in all proportions, at least up to 30 per cent., and Moissan has produced iron with 50 per cent. silicon in the electric furnace. This would seem to point to the nature of silicon being more like that of a metal than that of a non-metal. Another striking fact is the extreme chemical activity of silicon when alloyed with iron, in which it seems capable of existing in several different forms of combination. In this state it has a powerful affinity for oxygen, as seen in the Bessemer process. It also seems to promote the solvent power of iron for the gases usually present in that metal, hence its tendency to prevent blowholes.

Statements have been made from time to time that it exists in iron also in the graphitic form, but there is no proof that such is the case, indeed the properties mentioned above would tend to prevent such a separation occurring, except perhaps when the iron was in the molten state, and then any separated silicon would dissolve again in the iron on cooling. Moreover, the great affinity of silicon for iron is seen in the power it possesses of liberating carbon from cast iron, and limiting the amount of carbon that can be dissolved in iron. Silicon and carbon also unite when strongly heated

together, forming silicon carbide, SiC. When this carbide is formed in the electric furnace it is in the form of colourless crystals, and this compound has doubtless led some experimenters to confound it with crystallised silicon. Silicon makes wrought-iron harder.

Rubricius[1] found, on analysing samples of pig iron from the same cast, that the silicon varied considerably, being lowest in that part of the metal which is nearest to the bottom of hearth in the blast furnace, and richest in that part nearest to the slag hole. It is probably reduced from the slag and then enters the iron.

Silicon unites with sulphur to form the compound SiS_2, when sulphur, silica, and carbon are together at a white heat. The compound is volatile at a high temperature, and in moist air rapidly oxidises to silica with the formation of sulphuretted hydrogen. This is in accordance with the well-known fact that grey pig iron is freer from sulphur than white iron, and grey iron is the one that contains much the greater amount of silicon. Hence silicon tends to remove sulphur from iron.

Silicon affects cast iron in two ways: by causing the separation of carbon as graphite, and by uniting with the iron in the form of alloys, in which it is often in chemical combination. Prof. Turner[2] has made the subject of silicon in pig iron the basis of a long and thorough examination. As regards hardness, he finds that in iron containing carbon, or what he terms pure cast iron, the addition of silicon up to 2 per cent. reduces the hardness in proportion to the quantity of silicon added, and that there is little appreciable difference until 3 per cent. of silicon has been added, after which the metal becomes harder. Silicon is therefore used as a softener for the harder brands of pig

[1] *Jour. Soc. Chem. Indus.*, 1894, p. 889.
[2] *Metallurgy of Iron*, p. 195.

iron. The proportions of silicon in pig iron of the following approximate composition, namely: total carbon, 2 per cent.; phosphorus, 0·3; manganese, 0·5; sulphur, 0·04 per cent.; gave the following properties:

Maximum hardness,	under 0·8 per cent.
Crushing strength,	about 0·8 ,,
Modulus of elasticity,	,, 1·0 ,,
Density in mass,	,, 1·0 ,,
Combined crushing, tensile, and transverse strength,	,, 1·4 ,,
Tensile strength,	,, 1·8 ,,
Softness and working qualities,	,, 2·5 ,,
Lowest combined carbon,	under 5·0 ,,

In practice the size of the casting and the proportion of the other elements have an important influence. Silicon then in moderate quantity added to cast iron diminishes the hardness, increases the tensile strength, the resistance to crushing, the density, prevents the formation of blowholes and diminishes the shrinkage. In white iron it also diminishes the shrinkage, but an excess of silicon leads to increased shrinkage. Shrinkage appears to closely follow the hardness of cast iron, and as both hardness and shrinkage depend on the proportion of combined carbon they may be regulated by the addition of silicon. It exists in wrought iron as slag and as free silicon.

Ferro-Silicon is a compound of silicon and iron, with varying proportions of other elements. It is a hard, highly crystalline, silvery-white body, obtained by reduction of silicious iron ores in the blast furnace by using a high temperature of blast, and a high fuel consumption. As a rule ferro-silicons do not contain more than 15 to 16 per cent. of silicon, though some have been made with 20 to 30 per cent.

Ferrous oxide and silica unite in different proportions to form silicates. The slag produced in purifying pig iron is

a basic silicate of iron, having the approximate formula $2FeO . SiO_2$, and contains about 70 per cent. of iron. It melts at a white heat, becoming very liquid. This silicate is produced in the puddling process, and termed "tap cinder." When tap-cinder is heated with access of air for some time, and then the temperature considerably increased, a fusible silicate liquates out, known as "bull-dog slag," leaving behind a very refractory substance, chiefly ferric oxide, and termed "bull-dog," which is used for lining puddling furnaces. This oxide does not readily unite with silica when heated, but if carbon or a reducing agent is present, it will be reduced to ferrous oxide, which then unites with silica.

Iron and Sulphur.—A compound of iron and sulphur exists in nature as iron pyrites, FeS_2. Iron and sulphur readily unite when heated together, forming ferrous sulphide, FeS, with the production of great heat. Sulphur, even in very small quantities, has an injurious effect on wrought iron, making it red short, although the metal may be worked in the cold. In some cases as little as 0·03 per cent. has been found to be injurious, and probably in all cases 0·1 per cent. would render the iron unfit for welding and forging purposes, although it might be permissible in castings, which have not to be afterwards worked. The presence of sulphur in cast iron tends to cause the carbon to pass into the combined form, thus making the iron white, hard, and brittle. Sulphur may be prevented from passing into the iron by the presence of basic slags, silicon, and manganese; also high temperatures tend to remove it. The influence of silicon in removing sulphur has been already mentioned. Molten pig iron may have its sulphur removed by pouring it on to lime, as in the Saniter process. Sulphur is always present in the materials charged into the blast furnace, but very little of it passes into the iron,

especially when grey iron is being made. The sulphur present is removed either in the slag or along with the furnace gases. Potassium cyanide is a powerful agent in removing sulphur, and as this compound is present in the blast furnace, it may have something to do with the elimination of sulphur. In pig iron containing notable quantities of sulphur, the latter is somewhat irregularly distributed through the mass. Mr. Stead found that sulphur was differently distributed in different varieties of pig iron. In a haematite pig containing but little manganese, the sulphur was greatest in the middle portions, while in a pig with 2 per cent. of manganese the sulphur was greatest in the upper and outer portions.

Desulphurisation of Iron.—Lime is capable of removing much of the sulphur from molten iron, and Saniter has shown that a mixture of calcium chloride and lime in the space of half an hour completely eliminates sulphur from molten iron. Calcium chloride is very cheap, being obtained as a by-product in the ammonia-soda process. Fluor-spar in conjunction with lime has considerable desulphurising properties, but it exerts a destructive action on the basic linings of furnaces. In the Saniter process the mixture of lime and calcium chloride is put into the ladle, hot from a previous charge, and when molten cast iron is run in, the calcium compounds are melted, and rising upwards through the metal, remove the sulphur. Mr. Stead states: (1) that when sufficient lime is present in a furnace charge to combine with all the sulphur and silica (the temperature being sufficiently high) practically all the sulphur will be found in the slag and very little in the metal; (2) that, if other things remain constant, as the temperature falls, so as to produce pig iron of close texture, the sulphur increases, and when the temperature is just sufficient to melt the metal, most of the sulphur will be

found in the iron; (3) that the more basic the slag, the less sulphur will eventually be found in the iron; (4) that if manganese is present, and the temperature sufficiently high, less sulphur will pass into the iron, and a greater amount will be found in the slag. This property is now taken advantage of in producing basic steel.[1] Massenez's process consists of mixing pig iron poor in manganese and high in sulphur with iron containing a larger percentage of manganese, and but little sulphur, the manganese of the one unites with the sulphur of the other, forming sulphide of manganese, which rises to the surface of the molten metal in virtue of its lower specific gravity. Ponsard mentions that 80 to 90 per cent. sulphur may be removed from pig iron by adding and stirring ferro-manganese in the ladle at the time of pouring. It is found that 2·6 parts of manganese remove 1 part of sulphur, the sulphur passing into the slag. Mr. Stead states that when manganese is combined with sulphur in pig iron, these elements do not prevent carbon assuming the graphitic condition as they do when in combination with the iron separately.

Iron and Phosphorus.—Phosphorus exists in iron ores chiefly as phosphate of lime, $3CaO.P_2O_5$, but in pig iron, wrought iron, and steel it exists as phosphide, except in the enclosed slag, where it is present as phosphate of iron. It can, however, be removed from iron by strong bases, such as oxide of iron, oxide of manganese, alkalies, and alkaline earths, such as lime; and by basic silicates, alkaline carbonates, nitrates, and fluor-spar, in a strongly oxidising atmosphere. It is volatilised when phosphates are heated with carbon, but the presence of metallic iron tends to prevent this. Hence in the blast furnace, no phosphorus is volatilised with the furnace gases, and, for the most part,

[1] *Iron and Steel Institute Journal*, II., 1892.

the phosphorus present is found in the pig iron produced. In refining such iron in a basic process, such as puddling or in the basic Bessemer or open-hearth, the phosphorus is largely removed in the basic slag. Wrought iron containing 0·3 per cent. of phosphorus is not much affected in tenacity, but such iron is likely to break by vibration. 0·5 makes the iron cold-short, but not hot-short, and 1·0 per cent. makes it brittle. A little phosphorus improves the welding property of wrought iron, but the welded joint is not so strong as one free from phosphorus. It has a tendency to produce a coarse crystalline structure, which is a sign of weakness. Phosphorus in pig iron has little effect on the condition of the carbon, but it makes the metal harder and diminishes the colour of grey irons. It increases the fluidity of cast iron, and renders the metal more suitable for the production of fine castings. For good strong castings the amount of phosphorus should not exceed 0·5 per cent., and less for those of the highest quality. For fine castings, where strength is not of first importance, 1·5 per cent. or more phosphorus may be present with advantage. A moderate amount of phosphorus, while increasing the fluidity, also lessens the shrinkage of a casting. As a rule, the amount of phosphorus should not exceed 1·0 per cent.

Iron and Arsenic.—Arsenic occurs in many iron ores in small quantities, either as a sulphide, oxide, or arseniate. It resembles sulphur in many respects, being volatile, readily oxidisable, and uniting with iron to form arsenides and arseniates. The arsenic present in a blast furnace charge as arseniate is not volatilised, but, on its reduction, probably the arsenic passes into the iron. The quantity of arsenic present in pig iron seldom exceeds 0·1 per cent. in British irons. It is not removed from iron in puddling or in the steel basic processes. With larger quantities of

arsenic, as in some continental irons, it makes the iron red-short like sulphur, and tends to make the iron white. Arsenic exists in ingot iron and steel as an arsenide, and in weld metal in the slag as arseniate (see Steel).

Iron and Manganese.—Manganese is nearly always present in iron, as most iron ores contain manganese, but manganese is more oxidisable than iron and more readily forms a slag with silica. Its presence increases the power of iron to combine with carbon, so that the higher the manganese the higher is the quantity of combined carbon, hence manganese tends to the production of white pig iron. Keep considers that the presence of manganese in cast iron makes the iron more brittle, and increases the shrinkage. The fact that manganese causes the carbon to go into the combined form would naturally point to its having a hardening effect on cast iron, although manganese, by forming an alloy with iron, would harden it independently of the indirect effect due to carbon. Manganese in a blast furnace charge tends to prevent the sulphur present from passing into the iron. When manganiferous ores are smelted in the blast furnace the quantity of manganese which is reduced and retained in the pig iron, when a high temperature is maintained and a highly basic slag produced by the addition of excess of lime, is about 80 per cent. and 20 per cent. in the slag. Two varieties of manganiferous pig irons are produced, one containing from 10 to 20 per cent. of manganese, termed spiegel-eisen and the other with 50 to 85 per cent. of manganese, termed ferro-manganese. The smaller the proportion of manganese in the ore the less will be the proportion of manganese in the iron and the greater the amount passing into the slag.

Iron and Chromium.—The small quantities of chromium generally present in pig iron are negligible so far as they

influence the properties of cast iron, and when such iron is puddled for making wrought iron the chromium is readily oxidised and passes into the slag. Rich ferro-chromes are prepared by reducing chrome iron ore in crucibles. For reducing chromium in the blast furnace a very high temperature is required with a light burden of ore and three times its weight of coke. The slag produced is difficult to fuse. If 5 per cent. of chromium is present in the slag it is thick, flows very sluggishly, and is of a yellowish-brown colour. Ferro-chrome is very fluid when thoroughly melted. Chromium increases the solubility of iron for carbon considerably, and makes iron hard, white, and brittle. It does not appear to remove sulphur from iron like some other elements.

Iron and Vanadium.—Vanadium was found by Sefström in 1830 in Eckersholm bar iron, and is now found to be somewhat widespread. It occurs as oxide in iron ores and is reduced in the blast furnace, passing into the pig iron. Blum found a large percentage in a thin slag on the surface of pig iron made from Luxemburg minette. The slag contained 2·56 per cent. of vanadic oxide and the pig iron 0·015 per cent. of vanadium, which shows the ready oxidisability of vanadium. It appears to resemble phosphorus in some of its properties. It is often present in slags from the basic process.

Iron and Titanium.—Pig iron sometimes contains titanium, when obtained from ores containing that metal, which often occur along with iron ores. The titanium is either minutely disseminated through the iron or alloyed with it. Some analyses by Mr. Riley, of grey pig iron from Wiltshire, gave 1·15, 0·71, and 0·47 per cent. of titanium respectively. But iron smelted from titaniferous iron ore may be quite free from titanium. In 1877 Mr. Riley showed that the so-called titanium steel of Mushet con-

tained no titanium. Moissan has reduced titanium from rutile in the electric furnace by means of carbon. It contains 2 to 6 per cent. of carbon. Faraday failed to reduce titanium oxide, although he states that rhodium, and, imperfectly, platinum were melted in the crucibles he used. In 1742 Mr. Horne successfully smelted the titaniferous ores of Canada, and good steel was made from them, the virtue of which was ascribed to this particular ore, although this was before titanium had been isolated as an element. It is a noted fact that titanium iron ores are practically free from phosphorus, which may readily account for the good quality of iron produced therefrom. We may consider then that titanium steel exists only in name. What titanium occurs in the pig iron passes into the slag when the iron is refined. Titanium is most abundant in grey pig irons and seldom present in white irons. Pig iron containing titanium generally shows a peculiar black, mottled appearance on the fractured surface, probably due to the separation of a carbide containing titanium.

CHAPTER VI.

PIG OR CAST IRON.

In the indirect method of producing malleable iron, a crude product consisting of iron, carbon, silicon, phosphorus, sulphur, manganese, and very frequently other elements, such as copper, arsenic, titanium, chromium, etc., is first obtained; it is termed "pig iron," and is D-shaped in section, being roughly 3 or 4 inches square and about 3 feet long. Pig iron is arranged into a variety of classes, according to the colour, texture, size of the crystalline plates, and general character of the fractured surface.

When the pig iron is obtained entirely from ore it is termed "all-mine" pig, which is graded from Nos. 1 to 8, or more commonly from No. 1 to 4 for foundry purposes, and No. 4, mottled and white. In the southern parts of the United States nine numbers are used, viz., Nos. 1 to 3, foundry; 4 and 5 are termed Nos. 1 and 2 soft; No. 6, silver grey; No. 7, grey forge; No. 8, mottled; and No. 9, white pig iron. Nos. 4, 5, and 6 are silicious irons, containing 4 to 6 per cent. of silicon. In this country, that containing the largest grain and largest crystals of graphite is No. 1, and this is found to be richest in silicon. As a general rule, in passing through the series from No. 1 to white iron, the combined carbon and the sulphur

regularly increase, while the silicon steadily diminishes, when the samples are prepared under practically the same conditions. Although there is but little difference between pig iron and cast iron, the latter term is used to express the metal obtained by remelting pig iron and casting it into various moulds, while pig iron is simply a variety of cast iron, cast in a particular form.

When the metal ceases to be grey the numbers are not used, the iron being designated as mottled, either strong or weak, and white, in which, when manganese is present in quantity, the crystals are large and lustrous and the iron intensely hard; such a pig iron is termed spiegel-eisen. The lower numbers of grey iron are called foundry pigs, being used for castings. The higher numbers are termed forge pigs, being chiefly used for the production of wrought iron. Two other varieties are also made, which, owing to their comparative freedom from sulphur and phosphorus, are used for making Bessemer steel, and are termed Nos. 1 and 2 Bessemer pigs.

Grey iron requires a higher temperature to melt it than white iron, but becomes very liquid, and expands on becoming solid, which admirably adapt it for casting. White iron is less perfectly fluid and passes through an intermediate pasty stage before becoming liquid, and the same during solidification after fusion. It contracts considerably after becoming solid. Grey iron is produced at a higher temperature in the blast furnace than white, which tends to make it more impure. It sometimes happens that both kinds are contained in the hearth of a blast furnace at the same time; the white being the heavier goes to the bottom, and when the furnace is tapped flows out first in a sluggish stream, emitting brilliant sparks; the grey iron following runs perfectly liquid without sparks.

The mottled variety of pig iron is intermediate between

grey and white irons, and partakes of the properties of both. When broken it shows a veined or mottled appearance, as though the white iron were distributed in portions or veins in a matrix of grey iron, and according as the proportion of white iron increases the metal is termed strongly mottled.

Common white iron is produced when the furnace is charged with a heavy burden of cinders, *i.e.* slags from other processes, mixed with ore, and is then termed "cinder pig" as distinguished from metal produced from ore alone, which is termed "all-mine pig." Cinder pig is dull in colour, and presents a rough honeycombed appearance on the surface; it is very hard and brittle. White iron is also produced when easily reducible ores are employed, so that the charge can be reduced and melted rapidly, and the melted metal remains a shorter time in contact with the highly heated carbon. In such a case a greater proportion of ore to fuel is employed, and consequently a lower temperature obtained. The production of grey iron requires a temperature far beyond that of mere fusion, causing the reduction also of oxides, other than those of iron, such as silica. Such a condition is brought about by working with light burdens, that is, excess of fuel, and using very hot blast. Other things being equal, the iron will be grey if the slag is refractory, for the particles of carburetted metal cannot coalesce until the foreign matter has united with the flux to form a fusible slag, hence they remain longer subjected to the action of carbon and silicon, which latter element induces greyness in pig iron.

Pig iron consists of iron with upwards of 1·8 per cent. of carbon and various other elements in greater or less proportion, of which silicon is always present, and generally sulphur, phosphorus, and manganese. Constituents other than the above may be considered as impurities, unless

such elements are purposely introduced so as to produce brands of iron for specific purposes. In this way we may get chromium, tungsten, molybdenum, aluminium, etc., as chief constituents of the pig iron, or alloys of these metals with iron and carbon may be made in crucibles or special furnaces. In ordinary pig iron the proportion of elements other than iron is about 7 per cent., but sometimes very much more.

Cast iron when in the liquid state may be considered as a saturated solution of carbon in iron, which generally contains about 3 per cent., depending upon the nature and amount of other elements present. Chromium and manganese increase the solvent power for carbon, and silicon acts in the opposite direction. Iron with 20 per cent. of silicon only dissolves about 1 per cent. of carbon. It is, however, unusual to meet with less than 2 per cent. or more than 4·5 per cent. of carbon in cast iron. Up till recently the conditions of carbon in cast iron has been considered as existing in two forms, viz., as combined carbon in white iron, and as free carbon in grey iron. One thing is beyond question, that carbon does separate from iron in the form of crystalline graphite, and makes the iron grey in colour, but whether carbon does unite chemically with iron in the white variety or exists simply in solution in the iron, is not yet satisfactorily determined. It is probable, however, that a definite compound does exist, similar to, if not identical with, the free carbide, Fe_3C, in steel. Possibly there may be more than one compound, or more than one alloy, dissolved in the main mass of iron.

When cast iron is in the fluid condition its composition is probably uniform, except in the case of very grey pig iron, when graphite separates out in beautiful plates, termed "kish"; but on cooling, according to the rate at which it solidifies, the carbon will separate, or remain in

close union with the iron. When both conditions prevail, the iron has a mottled appearance, due to the carbon being partly in what is termed the combined form, and partly in the free form. Slow cooling tends to the formation of grey iron, and quick cooling to that of white or chilled iron. The production of white or grey iron respectively is not only due to rate of cooling, but also to the presence of elements other than carbon, some of which increase the solubility of carbon in iron, and others act in a totally opposite direction, hence, irons which are very white or very grey are not materially changed by rate of cooling, and mottled iron may be produced by the counteracting influences of oppositely tending elements. The different kinds of pig iron act differently when treated with acids. On dissolving white cast iron in hydrochloric acid, the carbon combines with hydrogen to form ill-smelling hydrocarbons, which are volatile. With nitric acid, white iron and the contained carbon are dissolved, imparting to the solution a characteristic brown colour. On the other hand, with grey iron, the carbon, being in the free form, is insoluble in the above acids, and is left behind as a black residue.[1]

Malleable Cast Iron.—When cast-iron articles of small section are embedded in powdered haematite, or other suitable iron ore, packed in iron cases and heated to a cherry-red heat for a few days, they become very malleable and are said to be annealed. There are two classes of malleable castings in general use.

1st. The older class is produced from white pig iron of good quality, preferably that from Cumberland haematite ore. The castings after cleaning are packed in iron boxes and completely covered with particles of haematite about $\frac{1}{8}$

[1] For fuller information concerning the properties of cast iron, see Turner's *Metallurgy of Iron.* Griffin & Co.

inch in diameter. The cases are then placed in the furnace, gradually raised to a red heat and maintained at that temperature three or more days, according to the degree of softness desired, and the character of the castings.

2nd. "Black heart" castings. These are malleable castings which retain the original carbon practically unaltered in amount in the central portion, but the carbon is changed from the combined to the graphitic form. The outside portions, however, contain less carbon than the interior. If a piece of malleable cast iron is strongly heated and quenched in water it becomes intensely hard, showing that the mass of the carbon is not removed by the annealing process but only modified.

Mr. J. Stead[1] has investigated the nature of malleable castings by operating with cast round bars. He found a transverse section taken from one end, $\frac{5}{8}$ inch in diameter, to consist of five different concentric zones. The outer one had a thickness of 0·072 inch, and consisted of iron and silica, the latter appearing to have been deposited in the joints of the iron crystals. The second zone consisted of iron free from carbon, but the iron was crystallised in a columnar form, radiating from the exterior surface towards the centre. The third zone is a mixture of iron and pearlite. The fourth zone appeared to be all pearlite. The fifth zone had the appearance of steel with 1·4 per cent. of combined carbon, and consisted of large meshes of cementite, with intervening pearlite and a considerable quantity of graphite.

It appears probable that, when white cast iron is annealed, the combined carbon in the form of pearlite is set free as graphite. If the alteration were confined to the surface it might be assumed that the carbon was burnt off; but the change goes right to the centre, and as much of the

[1] *Cleveland Inst. of Engineers*, Dec. 16th, 1895.

carbon is retained it proves that a soft and tough casting may be obtained by simply transferring the hardening carbon to graphite or temper carbon. When this change has been completely effected no advantage is gained by heating with fresh haematite, and the outer layer does not materially increase in thickness nor the central portion become more or less crystalline.

Turner[1] found that the powder after annealing had been partially reduced to metallic iron. He also found that haematite powder to a certain extent removes sulphur from the iron, probably by uniting with the reduced iron.

It was formerly considered absolutely necessary to have an oxidising material as the cementing powder, on the assumption that the carbon of the cast iron was removed by the oxygen of the cement, and the process was termed an oxidising cementation. Now it has been found that other materials of a non-oxidising character can be effectively used instead of oxide of iron, so that the change is chiefly due to the annealing. The process was formerly confined to comparatively small articles, such as light harness work, agricultural work, and hardware generally, but now it is applied to heavy work, such as railroad castings, couplers, and the like. In America, sand or fireclay is largely used as the cement. For small work the metal is melted in crucibles, and the output of an ordinary works is about 500 lbs. per day. In large works in America it is claimed that plants are arranged for an output of 50 to 75 tons.

The output of malleable iron castings is increasing considerably.[2] The reason for this rapid expansion is not hard to find. Malleable cast iron has a unique position in the iron industry. Softer than cast iron, it can be battered out of shape before it breaks. It surpasses steel in shock-

[1] *Metallurgy of Iron*, p. 242.

[2] *Engineering and Mining Journal*, Sept. 8th, 1900.

resisting qualities, for while a piece of steel may be strained within its elastic limit many times over without harm, if the strain extends beyond this range the piece is ruined. Not so with malleable cast iron. Take two couplers with their heads battered up in service, one a malleable cast iron, the other cast steel. A test piece cut from the tail of the former will show good sound material, while the latter has been so fatigued, lines of crystallisation opened, etc., that it may pull at one-third of the strength it should have shown.

Malleable cast iron may be twisted, bent, machined, polished, threaded and, in fact, treated just as ordinary iron and cast steel without detriment. It has eight times the shock-resisting qualities of the best cast iron, and is about one-half as strong as the best cast steel. It is, therefore, used where cast steel would be too expensive, and replaces cast iron, dollar for dollar, where strength is wanted, and castings of half the weight will answer.

The analysis of a piece of good malleable cast iron would be about as follows: Carbon (weighed as graphite), 2·5 per cent.; combined carbon, 0·10 to 0·60; manganese, about 0·25; sulphur, not over 0·07; phosphorus, not over 0·20 per cent. Its physical strength should be about as follows: Ultimate strength, 37,000 to 45,000 lbs. per sq. inch; elongation in 2 inches, 3 to 5 per cent.

The amount of carbon varies according to the thickness of the casting and the time of annealing. The following is typical of the various thicknesses:

Carbon per cent.,	0·15	0·64	1·03	1·6
Thickness in inch,	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{5}{16}$	$\frac{9}{16}$

The materials used in the manufacture of malleable iron castings are pig irons running low in silicon. Charcoal irons seem to give the best results, but only because they are much cleaner and more uniform than the general run of coke irons. A heat of good coke iron, however, especially

when steel scrap has been added, leaves nothing to be desired. There are used in this country to-day about equal proportions of coke, malleable iron, and warm-blast charcoal iron for malleable work. Charcoal iron goes to the account of the small companies and some unprogressive or favourably situated large ones; the coke iron forms the staple product of most of the heavy producers.

Malleable castings may be made either in the cupola or in open hearth furnaces. Owing to the closeness of the grain, a cupola iron is difficult to anneal properly, and this class of malleable cast iron is, therefore, restricted entirely to very thin sections. Cupola iron can, however, be made very hot by the use of plenty of coke (occasionally as much as 1 lb. of coke to 5 lbs. of iron). This enables the founder to run it into the thinnest kind of castings, such as shoe buckles, harness work, scissors, etc. Furnace iron, unless special precautions are taken, is apt to be somewhat dull at the first part of the tap, and should, therefore, go into very plain work, otherwise mis-runs are likely to occur.

On the other hand, during the melting process the oxidation of the silicon means an increase in the internal heat of the bath, hence more fluid iron, and the temptation is to cast light, intricate work at the end of the heat. Unfortunately, however, burning out silicon means introducing oxygen into the bath; pin-holes will appear on the surface of the castings, and if aggravated, there will be a burning of the iron in the annealing process, hence the danger of casting light work at the end of the heat.

The difficulties attending the preparation of malleable cast iron are so great that the whole process has largely remained a mystery to outsiders, and consequently only those who have become thoroughly familiar with every phase of the process are capable of accurately describing it.

The furnace processes are two fold : the plain hearth with or without top blast, and the regular Siemens open-hearth furnace. The capacity of the hearth furnaces is from 6 to 10 tons. They are fired from the end, the blast being admitted under the grate. Usually a branch pipe is placed so as to blow additional air downward at the bridge wall, thus throwing the flame upon the metal, and at the same time promoting a better combustion. It takes an hour to charge a 10-ton furnace, and after this the heat lasts from 4 to 6 hours.

With the open-hearth furnace the operation is somewhat different—the hearth being hot, a 10-ton heat can be got out an hour earlier. The castings, after knocking off the gates, are rolled up clean in barrels, or by the apparatus known as the "sand-blast," then sorted and placed in cast-iron boxes, termed " saggers," but for special purposes wrought iron pots are used. The articles are embedded in haematite or other cementing powder, which is generally of a fineness less than that of peas. It is not usual to use raw ore alone, but to mix it with ore that has been used in a previous operation, as all raw ore is found to work too rapidly. When the ore has been used several times it is considered to have its power of conversion diminished. The quantity of new ore added is about one-third of the cementing mixture, but for small articles somewhat more is added.

The saggers or pots are then placed into a rectangular heating chamber, or annealing oven, heated by a coal fire, or by means of gas from a producer. The temperature is gradually raised, and in about twenty-four hours it has attained to a cherry-red heat, which is maintained for another twenty-four hours or more, according to the size of the castings and the degree of conversion required.

The castings after annealing are again cleaned by barreling or sand-blasting.

The following rules are recommended in the production of malleable iron castings[1]:

I. Never run from a heavy to a light section.

II. As the strength of malleable iron is largely in the skin, expose as much surface as possible. A star-shaped section is the strongest possible form of a casting. For brackets, use a number of thin ribs instead of one thick one.

III. Avoid all round sections, as this is the weakest form. Avoid sharp angles.

IV. The shrinkage generally on castings will be $\frac{1}{20}$th of an inch to the foot.

ANALYSES OF PIG IRON.

From Haematite.

	I.	II.	III.	IV.	V.
Graphite, - -	3·52	3·10	3·40	2·16	2·60
Combined carbon,	0·18	0·40	0·25	1·05	1·20
Silicon, - -	2·85	2·40	2·60	1·10	1·78
Sulphur, - -	0·03	0·04	0·04	0·48	0·02
Phosphorus, - -	0·03	0·04	0·03	0·04	0·04
Manganese, - -	1·31	0·40	1·24	0·33	0·13
Copper, - -	0·11	0·08	0·10	0·11	—

No. I. is a sample of No. 1 grey pig. No. II. is a sample of No. 3 grey pig. No. III. is a sample of No. 2 grey pig; and No. IV. is mottled pig. No. V. is Bessemer pig.

From Clay Ironstone.

	I.	II.	III.	Forge.	Mottled.
Graphite, - -	3·20	3·25	3·10	2·72	1·99
Combined carbon,	—	0·25	0·46	0·80	1·45
Silicon, - -	3·50	1·13	1·09	0·97	0·85
Sulphur, - -	0·05	0·03	0·05	0·20	0·32
Phosphorus, - -	1·67	1·50	1·46	1·46	1·23
Manganese, - -	0·68	0·89	0·65	0·69	0·62

[1] *Iron Age*, Vol. xlvi., p. 44.

WHITE PIG IRON AND CINDER PIG.

	I.	II.	III.	IV.
Graphite, - -	0·87	0·12	2·60	} 3·55
Combined carbon, -	2·46	3·80	0·25	
Silicon, - - -	1·12	0·20	1·85	1·26
Sulphur, - -	0·52	0·22	0·14	0·35
Phosphorus, - -	0·99	0·33	1·56	1·05
Manganese, - -	0·42	0·55	—	0·79

Nos. I. and II. are white pig irons. Nos. III. and IV. are cinder pigs.

ANALYSES OF MALLEABLE CAST IRON.

	Combined Carbon.	Graphite.	Silicon.	Manganese.	Sulphur.	Phosphorus.
Average composition,	30·5		1·00	0·30	0·050	0·030
Before annealing, -	2·60	0·72	0·71	0·11	0·045	0·039
After annealing, -	0·82	1·75	0·73	0·11	0·040	0·039

SILICON AND PHOSPHORUS PIG IRON.

	I.	II.	III.	IV.
Graphite, - -	2·59	3·44	} 1·40	2·68
Combined carbon, -	0·79	0·21		
Silicon, - - -	5·13	4·89	12·05	0·11
Phosphorus, - -	1·12	0·06	0·04	3·29
Sulphur, - -	0·17	—	0·01	0·04
Manganese, - -	0·77	0·84	2·10	3·84

Nos. I. and II. are glazed pig. No. III. is ferro-silicon; and No. IV. is highly phosphoric pig.

MANGANIFEROUS PIG IRON.

	I.	II.	III.	IV.
Carbon, - - -	4·10	5·25	6·00	6·50
Silicon, - - -	0·25	0·46	0·50	1·50
Phosphorus, - -	0·03	0·08	0·10	0·30
Sulphur, - -	0·06	—	—	0·02
Manganese, - -	11·10	20·50	51·80	86·80

Nos. I. and II. are spiegel-eisens. Nos. III. and IV. are samples of ferro-manganese.

CHAPTER VII.

EXTRACTION OF IRON FROM ITS ORES.

PROCESSES for the extraction of iron from its ores may be classed under two heads, viz., "Direct" and "Indirect" methods, which are represented in a general manner in the accompanying scheme (Fig. 19).

In the *direct method*, the ore is reduced to iron or steel in arrangements such as the Catalan forge or Siemens rotator, then hammered, reheated, and finished with the hammer or rolls. In the *indirect method*, the ore is calcined, reduced in a blast furnace, run into pig moulds, puddled, hammered, rolled, reheated, and finished in the rolls for bar iron. If steel is desired, the bars are heated with carbon in the cementation furnace, then melted in crucibles for cast steel.

In the old method, the finery and open fire were used instead of the puddling and reheating furnaces.

Pig iron is treated in the Bessemer converter for Bessemer steel; in the Siemens furnace for Siemens steel; and melted in the cupola for foundry purposes. The bloom of iron produced in the rotatory furnace, or any similar method, may be made into steel by treating it in the Siemens open-hearth furnace.

Properties of Iron.—Malleable iron is of a greyish-white

colour, having a granular, crystalline, or fibrous fracture,

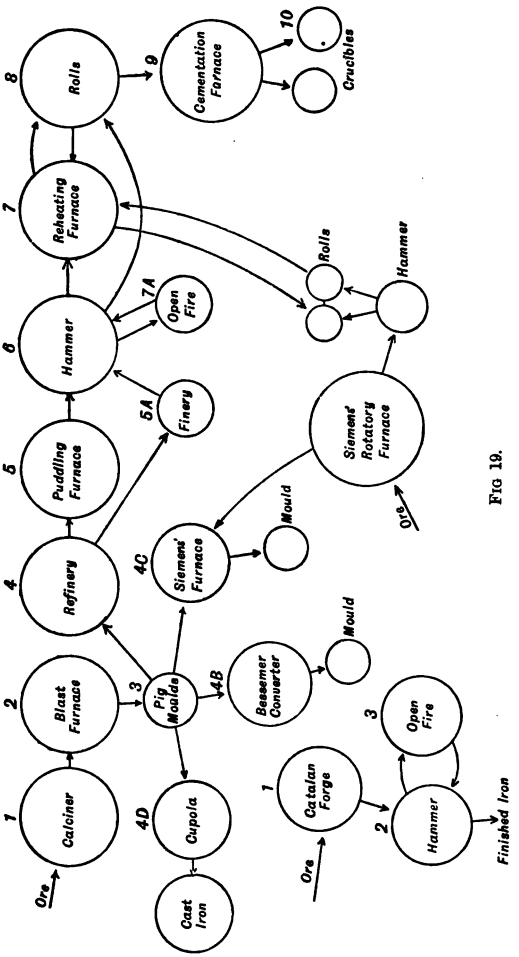


FIG 19.

according to the mode of treatment. When rolled or hammered hot the iron becomes fibrous, but continued

cold hammering induces a crystalline or granular structure, making it weak and brittle. The nature of the fractured surface varies also with the manner in which the iron has been broken, for specimens broken by progressively increasing stresses are invariably fibrous, while the same specimen broken by a sudden blow is generally crystalline. The presence of impurities generally tends to impart a granular or crystalline appearance on the fractured surface and makes the iron less malleable. When impurities, such as sulphur or oxide of iron, render the metal unworkable at a red-heat, it is said to be hot- or red-short. On the other hand, some substances, such as phosphorus, cause iron to crack when hammered cold, the iron is then termed cold short. The specific gravity of iron is about 7·8, and when the metal is compressed at a high temperature, the density is increased; but in wire-drawing and cold-rolling the metal elongates more than its transverse section diminishes, and the density is diminished, but its tenacity is increased. Its fusing point is said to be about 1600° C.; but before melting it assumes a pasty state, when two pieces may be joined together by welding. To ensure a good weld the surfaces must be clean, free from scale, and the metal at a white heat. In order to dissolve any scale the smith adds a little sand, which unites with the oxide and forms a fusible silicate. The presence of any foreign bodies, such as carbon, silicon, sulphur, phosphorus, copper, oxygen, etc., increases the difficulty of welding. Iron possesses considerable malleability, ductility, and tenacity. Its tensile strength ranges from 17 to 25 tons per square inch,[1] but this, like all the other physical properties, is

[1] According to Roberts-Austen the tensile strength of electro deposited iron is 2·7 tons per sq. inch before annealing, and 15·5 tons per sq. inch after annealing. (*Jour. of Iron and Steel Inst.*, 1880.)

modified by the presence of impurities, which tend to make it harder, more fusible, and brittle. When iron is heated to dazzling whiteness, it burns, forming some black oxide Fe_3O_4, the iron becoming friable and brittle, and is then termed "burnt-iron." Iron may be magnetised by bringing it in contact with, or near to a magnet, but it loses its magnetism when the exciting magnet is withdrawn. Its specific heat is ·1137, and its conductivity about 150, silver being taken as 1000. Its electrical resistance is 5·8 times that of pure copper. When iron is exposed to moist air it readily rusts or oxidises, so that it is often coated with some substance to prevent this action, such as tin, zinc, paint, etc., or by the black oxide of iron, as in the Bower-Barff process.

CHAPTER VIII.

PREPARATION OF IRON ORES FOR SMELTING.

IRON ores are sometimes subjected to preliminary operations preparatory to the smelting process, according to their nature and to the facilities for obtaining supplies. In parts of the world where good ores are abundant, such as in England, mechanical treatment of poor ores, such as washing, dressing, etc., offers but few advantages. On some parts of the Continent, where the opposite condition holds, poor ores are sifted, crushed or stamped, and washed, in order to remove the lighter impurities, such as sand, clay, etc.

For regularity of result in smelting, it is advisable to have the lumps of ore, fuel, and flux reduced to a uniform size, according to the capacity of the furnace, and the greater or less ease with which the ore is reduced. In the large Cleveland furnaces blocks of ore 4 to 6 inches in diameter are employed, while the hard magnetic ores of Sweden are reduced to $\frac{3}{4}$ or 1 inch cubes. Large pieces allow a freer passage for the gases; small pieces pack closer and offer greater resistance to the blast, but a greater surface is exposed to the reducing gases.

Weathering.—In some cases, such as the clay ironstones of the coal measures and ores containing pyrites, exposure to the atmosphere for a lengthened period causes oxidation

and disintegration of the shale and pyrites, whereby the former can be readily separated, and the latter are partially oxidised and washed away by water.

Magnetic Concentration.—Certain ores of iron are capable of being attracted by the magnet, and certain other ores may be made magnetic by suitable roasting. If such ores are crushed into small pieces and brought into the vicinity of the poles of powerful electro-magnets, the magnetic particles are pulled away from the non-magnetic portions, with the consequent separation of the more valuable ore from its associated gangue. Magnetites, being naturally magnetic, may be concentrated direct, but the various haematites and carbonates require a preliminary calcination. When such ores are calcined at a low red-heat, with the addition of 1 to 5 per cent. of coal in the case of red and brown haematites, they are converted to magnetic oxide of iron. Magnetic concentration not only removes much of the gangue, but also the greater part of the phosphorus compounds and certain of the sulphur compounds.

One of the simplest separators is the Wenström machine, which is capable of treating ores in fairly large pieces. In addition to ores, this machine is used for separating cupola residues from loam and sand; also for the recovery of cast iron shot entangled in blast furnace slag, etc. The material is fed on to a revolving drum from a jigging tray. The armature of the drum consists of a number of soft iron bars, each separated by a bar of wood. A central stationary field-magnet is fixed eccentrically with regard to the armature barrel. The bars of soft iron are internally placed, so that each successive bar becomes oppositely magnetised and thus exerts a greater attractive power on a piece of ore large enough to bridge the distance between them. The magnetic portion of the ore is carried round on the drum

until it is beyond the influence of the magnetic field, when it drops down a shoot, while the non-magnetic portion drops down in front of the drum.

The Monarch separator may be regarded as a Wenström machine with the drum duplicated. In this case the ore must be dry. It is fed on to one of the drums by a feed-roller, and all the material is made to pass close to the drum by means of a bent shield. The non-magnetic portions fall into a receptacle below and the magnetic particles are carried round till they are caught by the second drum, which is supplied with a stronger magnetic field than the first one.

The Edison magnetic ore separator was introduced for treating an ore with a felspathic gangue, containing 25 per cent. of magnetic oxide of iron. The ore is crushed with heavy rolls, and drops into a pair of intermediate rolls. After passing these, it is lifted to the top of the building, and passed through three more sets of rolls to reduce it to small pieces. It is now passed through a screen of "14-mesh," and then falls between powerful magnets, arranged in three tiers on the side of a specially constructed tower. The magnetic particles are deflected by the attraction of the magnets and pass to one side, while the tailings, being unaffected, fall perpendicularly to the bottom of the tower. The concentrates are dried, passed through a fine sieve and again submitted to the action of a smaller set of magnets. This is repeated with still smaller magnets, after which the concentrates contain about 67 per cent. of metallic iron. These are mixed with a certain proportion of binding material and compressed into briquettes of about 1 lb. each, ready for the blast furnace. All the bearings are oiled by a gravity feed from a central oil station. The dust is claimed to be an advantage as it protects the bearings, each of which has its own oil-cup.

Calcination.—This operation is resorted to in the case of all iron ores, except massive red haematites and certain magnetites. The effect of this is to decompose any pyrites, with the partial volatilisation of the sulphur; to eliminate carbon dioxide, water, and other volatile matter; to convert ferrous into ferric and magnetic oxides, which greatly reduces the liability to form slag with silica; and to remove carbonaceous matters, such as in blackband iron ores. Moreover the ore is rendered more porous, and more readily susceptible to the action of reducing agents. The loss of weight by calcination is from 15 to 50 per cent.

Ores containing pyrites can be very largely desulphurised by careful calcination, if sufficient air is admitted. But the materials must not be allowed to get too hot, so as to cinter by partial fusion, otherwise the sulphur and other volatile matters will only be partially removed. Sulphates are reduced to sulphides in the presence of reducing agents. Phosphates, such as phosphate of lime, are unaltered by calcining. The effect of overheating, or deficiency of air is seen in the black and clotted appearance of the ore as it comes from the calcining chamber.

Calcination is performed in heaps, in stalls, and in kilns. The first method is adopted in localities where fuel is cheap and space abundant. The ground is first covered with a layer of coal a few inches thick, then a layer of iron ore 12 inches thick; this is succeeded by fresh layers of coal and ore, the whole heap varying from 3 to 9 feet high. Fire is then applied at the base, and the combustion gradually extends to the whole mass, 3 cwts of coal being required for 1 ton of calcined ore. Blackband ironstone often contains sufficient carbon to effect the calcination without additional fuel, except the layer of small coal at the base.

Calcination is conducted in some districts in stalls, each

of which consists of three vertical walls enclosing a space, into which the ore is placed. Draught-holes are left at suitable intervals for the passage of the air. This forms a kind of rough kiln.

Calcining in kilns is much more preferable than the preceding method, as the fuel is more perfectly utilised and a more uniform product is obtained. They occupy less space, are continuous in action, and can be placed near the blast furnaces. They save labour, as the ore can be carried to the top by mechanical means. The ore is also protected from the weather, wind, snow, rain, etc. The process is more under control, and the fuel consumption less, as there is less loss by radiation, and the heat is more fully utilised.

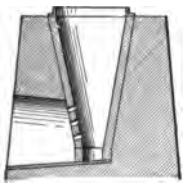


FIG. 20.

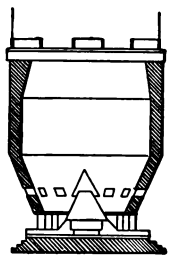


FIG. 21.

In South Wales the kiln shown in section, Fig. 20, is in the form of an inverted truncated cone 15 to 18 feet high, 20 feet long, 8 to 9 feet wide at top and 2 feet wide at the base. Two arched passages, splayed outwards, are left at the base for withdrawing the charge. At a height of a few feet above the top is a railroad supported on pillars, over which the loaded wagons pass, and deliver their contents into the kiln in alternate layers of ore and fuel.

One of the best forms of kiln is that of Gjers, Fig. 21, largely used in the Cleveland district. The body is of fire-brick cased with wrought iron plates. The diameter at the

base is about 14 feet, at the boshes about 20 feet, and at the top about 18 feet. The bottom of the brickwork rests on cast-iron plates, and the whole is supported on cast-iron pillars. In the centre of the base of the kiln is a cone about 8 feet high, and the same in diameter at the base. The total height of the kiln is about 30 feet, and the capacity about 6000 cubic feet. From two to three days are required for the calcination, with the consumption of 1 cwt. of coal per ton of ore. As the calcination becomes complete, the ore is discharged at the bottom between the pillars, being directed outwards by the cone. The calcination is carried on continuously.

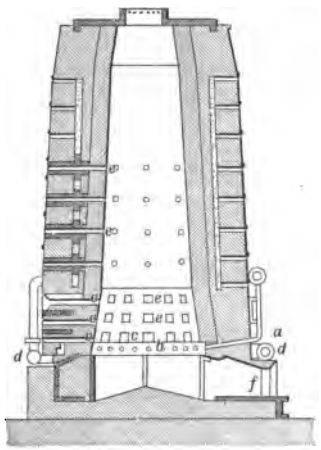


FIG. 22.

Fig. 22 represents a Swedish kiln about 20 feet high, employing the waste gases of the blast-furnace as a source of heat, instead of solid fuel. The combustion is effected by means of a blast of air introduced through the twyer (*a*), which communicates with the annular space (*b*), from which the air penetrates into the furnace by a number of small openings. The gas is conveyed by the pipes (*dd*), and enters the kiln by the channels (*e*). Above these are other channels (*ee*) which are kept closed; these are used for introducing bars to break up any lumps that may have caked together, or to admit additional air if necessary. The calcined ore is discharged through five radial openings (*f*). The charging is performed at the top,

which is surmounted by a chimney for regulating the draught.

Hoffmann's calciner is designed to utilise the whole of the heat generated by the combustion of the fuel, thereby

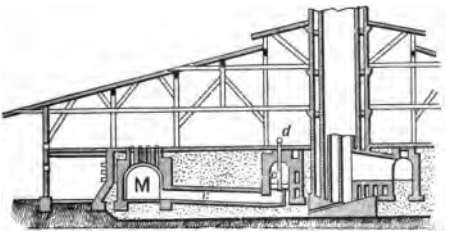


FIG. 23.

effecting a considerable saving. It differs from a barrel furnace with regard to the direction of the gaseous current and the stationary condition of the solid matter. The

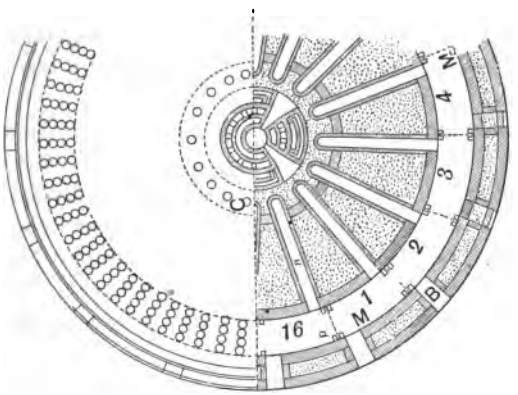


FIG. 24.

combustion is conducted in a horizontal direction in the same order as the gas. Figs. 23 and 24 represent a circular furnace of this kind in plan and section. The calcining space is annular, and is roughly divided into sixteen compartments (*MM*) by means of projections raised towards

the roof. The whole annular space is divided by means of a wrought-iron door (*p*). In Fig. 24 this door divides No. 16 from No. 1 compartment. A lateral opening or doorway (*B*) is also provided for each chamber for the purpose of discharging the calcined ore, but is bricked up during the operation, only two being open at one time—one being charged and the other being discharged. The air for combustion is drawn through these doorways, and passes in the direction of the chambers 3, 4, 5, 6, etc. Each compartment communicates with the central gallery (*C*), and thus with the chimney by means of inclined flues (*n*), each of which is provided with a damper (*d*); all these are kept closed, except that connected with No. 16. Along this flue the products of combustion finally pass into an interior circular space (*C*), termed the smoke-flue, which communicates with the chimney. The outer wall is double, about 3 feet thick, the two portions being separated by a space filled with sand, in order to close up any cracks produced by heat in the brick-work.

The cold air, as before mentioned, passes into the calciner at Nos. 1 and 2, then circulates through 3, 4, and 5, containing ore already calcined, the air being heated at its expense. The air then arrives at No. 6, where the ore is red-hot. The fire commences here and occupies No. 7 and part of No. 8. This is the zone of greatest heat. The gases then traverse the remaining chambers, giving up their heat to the matter being calcined.

The fuel is charged in small quantities through openings in the roof, when it inflames immediately, and burns without smoke, because of the high temperature of the air employed for its combustion, and the incandescent space into which it arrives. The same openings are only used for charging every 24 hours, a fresh range being opened every 4 hours, working in the direction of the general

current. Every 24 hours the operation in one chamber is completed. Then the iron partition (*p*) is transferred from No. 1 to No. 2, the doorway of No. 1 closed and that of No. 3 opened. The damper of No. 16 is then closed and that of No. 1 opened. Now the contents of No 3 are discharged and the chamber No. 2 refilled. The operation is thus continuous, and only stopped in the case of serious repairs. This furnace is chiefly used for baking bricks and burning limestone. An oval form is also in use.

The following analyses show in a general manner the composition of clay ironstone before and after calcining:

	Before.	After.
Ferrous oxide,	45·0	—
Ferric oxide,	2·0	70·5
Manganese oxide, Lime, Magnesia,	5·0	7·5
Carbon dioxide,	26·0	—
Water,	2·0	—
Alumina,	6·0	8·0
Silica,	10·0	12·0
Other bodies,	4·0	2·0

CHAPTER IX.

DIRECT METHODS OF MAKING MALLEABLE IRON.

WHEN malleable iron is extracted from the ore in one operation the process is said to be "direct." Many attempts have been made in recent years to revive the ancient principle of direct extraction, but the blast-furnace has been brought to such a pitch of excellence as regards economy of materials, and the perfection of its reducing action, as to outstrip all rivals.

In reducing the ore directly, two things have to be taken into account: 1st, the easy oxidation of iron by carbon dioxide and water, at the temperature at which ferrous oxide is usually reduced to the metallic state by carbon, carbonic oxide, or hydrogen; 2nd, the facility with which iron at a red-heat combines with carbon. Now if gaseous fuel be employed as a source of heat and reducing energy, carbon dioxide and water will be produced, and a large excess of unburnt gas would be required to neutralise the oxidising tendency of these bodies, and this excess would require to be increased with the temperature. Sir L. Bell states that at a temperature near whiteness, iron will be oxidised, if carbon dioxide and carbonic oxide are present in equal proportions, and that when the volume of carbon

dioxide, CO_2, to carbonic oxide, CO, is as 11 to 100, the reduction of protoxide of iron is no longer possible. In other words, gas ceases to be useful as a reducing agent, when it contains one-tenth its volume of burnt gas. This enormous volume of unburnt gas not only represents a great waste of fuel, but also a great quantity of heat is absorbed in raising it to the requisite temperature, which can only be done by strongly heating the whole of the gas previous to its partial combustion. In the blast-furnace the combustion of solid carbon to carbonic oxide produces the requisite temperature, without producing an oxidising atmosphere, which makes that furnace unequalled for reducing energy.

With regard to the second difficulty, viz., the readiness with which iron combines with carbon at a red-heat. If solid carbon be employed to reduce oxide of iron, then only the exact quantity of carbon for such reduction must be added, in order to avoid carburisation of the iron, and the operation must be performed in a closed vessel, heated from the outside. But for this purpose the ore must be broken small, the flux and reducing agent well mixed with it, and the temperature maintained for a long time, with a considerable expenditure of fuel.

In all direct processes malleable iron can only be produced, by sacrificing a considerable portion of the iron, which passes into the slag, and this loss is in inverse ratio to the amount of carbon taken up by the iron. On the other hand, the blast-furnace allows of the most perfect utilisation of the fuel, and the slags produced therein are practically free from iron. Moreover, the pig-iron produced can be converted into malleable iron or steel in the Bessemer-converter, without an additional expenditure of fuel.

Catalan Process.—This primitive method of making iron

is now practically obsolete, only being retained in remote districts where there is an abundant supply of wood fuel and rich ores, as in the Pyrenees. It consists of a hearth made of sandstone, and lined with charcoal (Fig. 25). The back and opposite walls are faced with iron, and of the remaining sides, one is of rough masonry, and the other, which forms the working side of the furnace, consists of two iron plates, the lower one having a hole for tapping the slag. The top of this plate serves as a fulcrum for the workman's tools. The twyer is made of sheet copper, and generally inclines at an angle of from 30 to 40 degrees, according to the degree of carburisation desired. The blast is supplied by a blowing apparatus called a trompe (Fig. 26). The water falling down the pipe *A*, drags air through the inclined openings *BB*. This mixture of air and water falling into the cistern is divided into two streams, the air rising and passing forward into the twyer, the water running out of the cistern at *C*.

FIG. 25.

Haematites and magnetites are generally smelted without previous calcination, but carbonates are first calcined. The ore in small pieces is charged in with charcoal, several

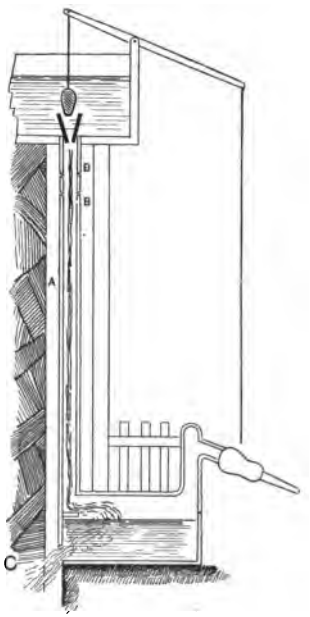


FIG. 26.

lumps of charcoal being placed near the twyer. The heat is gradually raised until a pasty mass is formed, which is then pushed towards the twyer. After two hours the full blast is turned on and the slag tapped off. The slag is fluid and formed at the expense of the iron; it is a silicate of iron ($2FeO,SiO_2$), containing lime, magnesia, and oxide of manganese, which composition is favourable for the transference into the slag of any phosphorus that may be present. When the whole of the ore is reduced, the blast is stopped, the spongy masses of iron worked into a lump with iron tools, then carried to the shingling hammer and shingled in order to squeeze out the slag and consolidate the porous mass of iron. It is then reheated in a similar fire, and the iron finished under the hammer. If the operation is prolonged and the twyer arranged at a smaller angle than in the above case, the iron combines with a certain amount of carbon and forms steel. The conditions governing the formation of slag in this hearth are similar to those of the puddling furnace and the reverse of those in the blast furnace, the former having an oxidising tendency and the latter chiefly a reducing one.

The chemical changes occurring in the Catalan process may be briefly stated thus: The air introduced by the twyer, being brought in contact with red-hot charcoal, causes a brisk combustion, with the formation of carbon dioxide, CO_2. This gas on ascending through other highly-heated charcoal is reduced to carbonic oxide, CO. The latter being a reducing agent acts on the ferric oxide, Fe_2O_3, which is partly reduced to the metallic state, and partly to ferrous oxide, FeO, which unites with silica and other foreign matters to form the fusible slag mentioned above.

American Bloomery, Jersey-, and Champlain Forge.—This simple method, employed in some parts of the United

States and Canada, is a modified form of the Catalan process, and is conducted in much the same manner, except that the ore is in a finer state of division, and the furnace is worked continuously.

The furnaces are built in rows on either side of a wall, each measuring about 28 × 30 inches in area, 25 inches in height above the twyers, and 14 inches below them. The sides are formed of cast-iron plates, and the bottom of beaten earth or cinders. In some cases a hollow iron bottom, cooled by water, is used. A water-box 12 inches by 8 inches is let into the twyer plate, and the water, after cooling the twyer, passes through the bottom plate. The twyers are arranged so that the blast strikes the middle of the hearth. In front of the forge, 16 inches above the bottom, is a flat iron hearth 18 inches wide, and in the side plate beneath it is a tap-hole for withdrawing the slag. The blast is used at a pressure of $1\frac{1}{2}$ to $1\frac{3}{4}$ lbs. per square inch, and heated to 300° C. by passing through cast-iron pipes in chambers arranged above the hearth.

The fire being made up, the forge is heaped up with charcoal, and crushed ore is scattered over the fuel. The ore is gradually reduced, without melting, as it descends, and the reduced grains collect into an irregular mass at the bottom of the hearth. The earthy matters at the same time separate as slag. Fresh supplies of ore and fuel are added from time to time, and in about three hours a mass, weighing 300 lbs., termed a "bloom," is lifted and held before the twyers for a few minutes, then carried to the hammer and shingled. It is then reheated and fashioned into bars. Sir L. Bell says that such a process can only be conducted where high prices, fostered by protective duties, prevail, and where it would be inexpedient to incur the large outlay involved in the erection of modern ironworks.

The Chenot Process was introduced about the year 1855, and was considered a great metallurgical discovery, but after a few years' working it was abandoned, except in one locality in Spain, where its continuance depended on the production of a quantity of charcoal screenings which would otherwise have been wasted.

The furnaces are rectangular retorts built in pairs—4 feet 6 inches long, 1 foot 8 inches wide, and 33 feet high. Beneath each retort is a rectangular tube of the same section, into which the metallic sponge is discharged. The total height of retort and tube is 50 feet. At the junction of the two parts are arranged four fireplaces, the flames from which circulate round both furnaces by a series of channels, which unite near the top and pass into a common flue. This mode of heating is very imperfect, as more heat is lost outside than passes into the retort. Four tons of fuel are required for the production of 1 ton of merchant-bars, and about 45 per cent. of the iron is lost. The retorts are charged with ore, broken small, and mixed with charcoal. The reduction extends over three days, producing a spongy mass of metallic iron, which requires three days to cool out of contact with air, to prevent rapid oxidation. The sponge obtained is made into steel by melting in crucibles with carbon; or is balled in a charcoal hearth, then hammered, piled, reheated, and rolled into bars of wrought iron.

Blair's Process.—In 1873 Mr. Blair in America introduced the Chenot process on an improved plan, but the furnace was irregular in its action, and the production small compared with that of the blast-furnace. The retorts are cylinders 3 to 4 feet in diameter and 40 feet high. The great difficulty was to cause the heat to penetrate successfully to the centre. In order to effect this, Blair placed in the top of each retort a concentric cylinder, and

through its axis a double blowpipe, by means of which a current of gas and air was forced in, producing by its combustion sufficient heat to make the ore and charcoal, charged into the reducing cylinder, red-hot.

Fig. 27 represents in section and plan one of a group of three furnaces. *A* is the retort, *C* the cylinder, *D* the gas-pipe, *E* the air-pipe, *F* the charging-space, *G* the annular space for combustion of the gas, *K* the gas-main, which introduces the gas at two different levels. This gas was originally obtained from the reduction

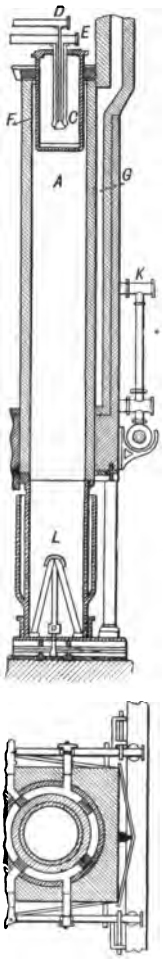


Fig. 27.

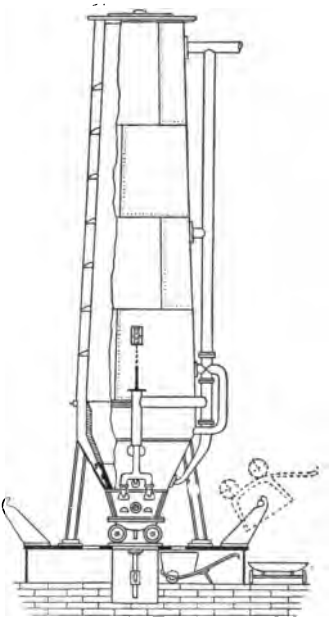


Fig. 28.

of the ore, but its amount being found insufficient, a special gas-producer was afterwards provided. The cylinder *L* beneath the reduction chamber receives the sponge of iron, and is kept hermetically closed while the iron cools, as in the Chenot furnace. The wrought-iron walls are double, in order to allow a current of water to circulate through them.

Husgafvel Process.—Husgafvel in 1875 commenced improvements in the old Osmund furnace, and finally adopted a movable cast-iron hearth; he also increased the height and capacity of the furnace with advantage.

The furnace (Fig. 28) consists of a wrought-iron shell surrounded by another wall or shell, the space between being divided by spiral partitions, thus forming a spiral flue around the furnace. The blast passing through this flue is heated to 200° C., and is regulated by dampers. It has four twyers, two on each side of the hearth, with two holes to each twyer. The hearth stands on a platform, which can be raised or lowered a few inches, to allow of the production of a tight joint. The interval between the hearth and furnace is luted with clay. The slag is tapped into a car through four holes, one above the other in the movable hearth.

The charge to produce 1 ton of iron is 1·6 tons of lake ores, 1 ton of puddling cinder, and 160 bushels of charcoal; part of the phosphorus goes into the slag, and the blooms are melted in a basic Siemens' furnace. The blast in passing between the walls of the furnace cools the materials in the furnace, and thus concentrates the reducing zone in the lower part, consequently, the reduced iron has not time to take up much carbon. Also the reduced iron sinks through the slag, and the carbon is thus oxidised. If steel is desired the temperature of the lower part is raised, and the inclination of the twyer diminished. If

the furnace is working too fast, or with too much ore the slag has a yellowish-red colour, indicating great loss of iron; with increasing carburisation on the other hand, the slags become less fluid. The amount of iron in the slag varies from 18 per cent. with very soft iron, to 7 per cent. with hard iron or steel. Also with soft iron two-thirds of the phosphorus is removed in the slag; while hard iron is rich in phosphorus. With iron low in carbon, oxygen is likely to be absorbed and make it red short. If magnetites are used in the Husgafvel furnace, they must be crushed small.

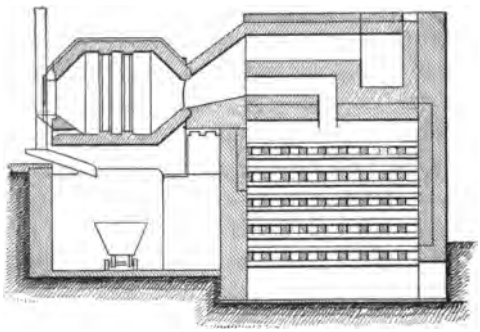


FIG. 29.

Siemens' Direct Process.—This is one of the modern attempts to extract iron in an economical manner from the ore in one operation, but it suffers under the disadvantages of all direct methods, as previously explained. It is not now used.

The furnace (Fig. 29) consists of a cylindrical rotating chamber, 10½ feet in diameter, and about the same in length, and rests on four anti-friction rollers. The inside is lined with bauxite, which consists of alumina, ferric oxide, water and a little silica. From this substance, when mixed with 3 per cent. of clay and 6 per cent. of plum-

bago, the lining bricks are made. The working door is at one end, and beneath this is a tap-hole for slag. The furnace is heated with gas supplied from a gas producer, the air being heated by passing through one of a pair of regenerators. Ore in small pieces is charged into the hot furnace with lime, and the cylinder rotated. When red-hot, about 20 per cent. of small coal is added as the reducing agent, and the velocity increased. The carbon and hydrogen of the coal, together with the carbonic oxide of the gas, react on the oxide of iron, removing its oxygen and liberating metallic iron, the particles of which gradually cohere to form a spongy mass, called a bloom. The lime and some of the basic lining of the furnace unite with the silicious matters to form a slag, which, in consequence of its basic character, is highly favourable to the taking up of any phosphorus that may be present in the ore. When the reduction is complete the slag is tapped off; then a quick rotation is imparted to collect the iron into three or more balls, which is effected by means of ribs or knees projecting from the lining. The balls are then shingled, reheated, and finished in the usual way. If steel is desired, 10 per cent. of spiegeleisen is added after tapping off the slag. The charge is then melted and cast into moulds. In some cases the balls were treated for steel in the open-hearth furnace. The advantages claimed for this method are—economy of time, saving of fuel, and purity of the iron, since the metal is not brought in contact with solid fuel, as in the blast furnace, except the coal added as a reducing agent.

At the back of the rotating chamber is fixed a water-jacket to keep the ring cool. In order to maintain the circulation of water, and also to turn the charges over as the vessel revolves, four water pipes pass beneath the lining from back to front of the rotator, connected

alternately with a valve at the front end, and the water-jacket at the back. Each pipe has two bends or knees, the lining of which stands above the general level of the furnace lining. These knees serve to divide the bloom of iron at the conclusion into three balls, as stated above.

Eames' Direct Process.—This process was introduced by the Carbon Iron Co. of Pittsburg, and is based on much the same principle as that of Siemens' rotator method. The ore is reduced by graphite from Rhode Island, having the following percentage composition: Carbon, 78; volatile matter, 2·6; silica, 15·06; phosphorus, 0·045; earthy matter, 4·29. This material is mixed with ore in the proportion of 2240 lbs. of dry ore to 550 lbs. of graphite. The mass is moistened with water to bind it together. It is placed on a flat hearth, 22×5 feet, with a stack at the centre of the furnace. The furnace bottom is simply a layer of 8 inches of graphite upon the brick-work. The charge is spread over the bottom to a depth of 4 inches, and a reducing flame of natural gas is allowed to play over the charge from jets at both ends of the furnace. Balling up is commenced after $1\frac{1}{2}$ hours, the reduced iron being made up into lots of 100 to 150 lbs. each. Each furnace will produce 12 to 15 of these balls. In half an hour the balls are taken to a rotary squeezer and then rolled into rough bars. Or they are taken hot to the bed of an open-hearth furnace. The time of an entire operation is about $2\frac{1}{2}$ hours, if the balls are to be used in the open-hearth, or three hours if for rolling. For open-hearth work each furnace will deliver, per twenty-four hours, eight heats of balls, weighing 1200 lbs. per heat.

The principle of the process is that the peculiar graphite used does not burn out rapidly, but adheres to the iron in considerable quantities, protecting it, and allowing the balls

to become compact, and when taken to the squeezer they do not readily oxidise, but can be further treated without severe loss. In this process the cost of the preliminary grinding of the ore is considerable, and the blooms, after squeezing, contain about 93 per cent. of iron. This in England would cost about 95 shillings per ton.

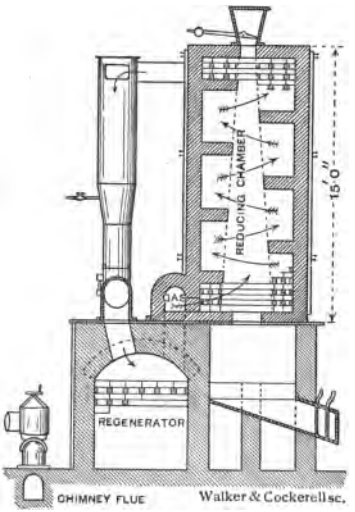


FIG. 30.

Adams or Blair-Adams Process.—An important modification of this process has recently been introduced in America, in which form a mixture of fine ore, with about 15 per cent. of coal, is charged into a vertical rectangular chamber (Fig. 30) which is tapered to allow of the ready descent of the charge. Reducing gas enters through a number of openings at the sides of the vertical chamber, and assists in the reduction of the ore. This gas is first heated to about 568° C. by passing through regenerative chambers. The reduction is accomplished in about five hours, no temperature

above a red heat being employed, and the chambers are sufficiently large to hold the materials necessary to produce 20 tons of iron: so that nearly 100 tons of malleable iron can be produced in twenty-four hours. This furnace has been worked at Pittsburg, and the iron produced has been transferred directly to the hearth of a Siemens' steel furnace. It may, however, if desired, be allowed to cool in a closed chamber.

The ore is introduced through the hopper at the top, and passes into the taper reducing chamber, through which reducing gases pass in the direction shown by the arrows, the gas afterwards passing down to the regenerators below. The spongy mass of iron produced is received into the cooling chamber at the base of the retort, and when sufficiently cooled can be compressed, either reheated and rolled into bar iron, or melted for the production of steel. In the latter case the reduction is accomplished by gaseous material.

CHAPTER X.

INDIRECT METHOD OF EXTRACTION.

Reduction in the Blast Furnace.—The calcined ore is put into the blast furnace with coal, coke, or charcoal, and a suitable flux, which is usually limestone. The weight of such materials is about 4 tons to produce 1 ton of iron and $1\frac{1}{2}$ tons of slag. The heat is well utilised, and the reduction more perfect than in any other form of furnace. In the blast furnace there are two currents travelling in opposite directions, and constantly acting on each other—a "gaseous" ascending current and a "solid" descending one. The former travels at the rate of about 3 feet per second, and the latter at the rate of 3 feet per hour. The effect of the blast on the carbon of the fuel is to produce carbonic oxide, CO., with the evolution of great heat. This carbonic oxide is the principal reducing agent in the blast furnace, the oxide of iron being reduced to the metallic state thus:

$$Fe_2O_3 + 3CO = 3CO_2 + 2Fe.$$

The flux and the earthy matter of the ore and fuel unite to form a slag, which descends with the iron; the latter in contact with highly heated carbon is carburised, then melts and collects in the hearth, where, in combination with other substances, such as silicon, phosphorus, sulphur, and manganese, which have also been reduced, it afterwards

constitutes pig iron. On the top of the molten iron floats the liquid slag. The general temperature and pressure have a great influence on the reducing action, and as the temperature increases with the temperature and pressure of the blast, it follows that as the reducing energy becomes greater the metal is more impure. The waste gases passing from the top bear a relation to the amount of blast introduced at the bottom of about 1·3 to 1, so that 30 per cent. more gas leaves the furnace than is introduced into it by the blast.

When very pure iron is desired, rich haematite and cold-blast are used, with charcoal as fuel. Great advantage is gained by the use of hot air, as less carbon is required for reduction and fusion. It is also useful to remedy defects, and to regulate the passage of materials through the furnace. If the fusion or reduction is at fault the temperature of the blast is raised, or more carbon is added to the furnace. The former acts promptly, while the latter often takes several hours to remedy the defect.

The quality of the pig iron produced from a given furnace will depend on the temperature, the nature of the charge, and the mode of working. With easily reducible ores and heavy burdens—that is, with a large proportion of ore to fuel—the iron will be white, since the metal is kept only the minimum time in contact with incandescent carbon. With a high temperature and a light burden the pig iron is more silicious and grey. The same things influence the character of the slag. Blast furnace slags are double silicates of lime and alumina, and may be represented by the formula

$$3(CaO,SiO_2) + Al_2O_3,3SiO_2,$$

or

$$6(2CaO,SiO_2) + 2Al_2O_3,3SiO_2.$$

The former is the kind of slag obtained from charcoal furnaces, and the latter from furnaces using coke or coal. In

both cases the lime is replaced more or less by magnesia, oxide of iron, and oxide of manganese; while the silica is sometimes replaced to a small extent by alumina. The colour varies from white to grey, sometimes with varying shades of yellow, green, blue and black, according to the metallic oxides present. Generally a white or grey slag accompanies grey iron, and a dark-coloured slag, white iron. The former slag often contains excess of lime, which diminishes its fusibility; the latter is more fusible, and contains oxide of iron, which, when present in quantity, makes a very liquid "scouring" slag or scoria. (That is, one capable of attacking the lining of the furnace. A scouring slag may contain as much as 20 per cent. of iron.) When forge or mill cinders are added to the charge, the resulting metal is called cinder pig iron, and the change produced by the reduction of such slags may be represented by the following equation:

$$3(2FeO \cdot SiO_2) + 4C = (2FeO \cdot 3SiO_2) + 4CO + 4Fe.$$

When oxide of phosphorus is present in the blast furnace it is reduced, and the phosphorus passes into the iron, but this can be partially prevented by allowing much oxide of iron to pass into the slag.

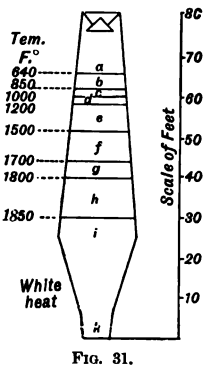


FIG. 31.

The temperature and condition of the charge in different parts of a blast-furnace are represented by the aid of Fig. 31, prepared by Sir L. Bell. The zone (*a*) contains the raw materials; in (*b*) the ore is partially reduced by carbon; and in (*c*), which is at a dull red-heat, the limestone added as a flux is decomposed into lime, CaO, and carbon dioxide, CO_2, which is liberated, thus:

$$CaCO_3 = CaO + CO_2.$$

In the zone (*e*) carbon dioxide, CO_2 oxidises carbon from the fuel forming carbonic oxide, CO; and in (*f*) which is at a bright red-heat, the reduced iron takes up carbon, forming cast iron. This action is continued in the lower zones, in which foreign oxides, such as silica and phosphoric acid, are also reduced; the silicon, phosphorus, etc., uniting with the iron. In the zone (*i*) the temperature is very high, the iron is thoroughly fused, as well as the slag formed by the union of the flux with the earthy matter. In the zone (*k*) the temperature attains to intense whiteness; here the molten materials separate according to their specific gravities, the iron falling to the bottom, and the lighter slag floating on the top.

Although carbonic oxide has been spoken of as the chief reducing agent, it must not be supposed that the action of carbon is unimportant, for it plays a prominent part both as a reducing agent and as a carburiser. Carbonic[1] oxide never completely reduces oxide of iron, and at high temperatures it even oxidises iron, especially if in the spongy form. Carbon dioxide oxidises hot iron energetically, and if in sufficient excess will probably produce ferric oxide. These actions are shown in the following equations:

$$(1)\ \mathrm{Fe} + x\mathrm{CO} = \mathrm{FeO}x + x\mathrm{C}.$$

$$(2)\ \mathrm{Fe} + x\mathrm{CO_2} = \mathrm{FeO}x + x\mathrm{CO}.$$

$$(3)\ \mathrm{FeO}x + y\mathrm{CO_2} = \mathrm{FeO}\overline{x+y} + y\mathrm{CO}.$$

If then, iron, oxygen, and carbon, however initially combined, are exposed to a high temperature, the oxygen tends to distribute itself, according to the conditions required for equilibrium, depending on the temperature, proportion of iron to carbon, etc. It will be seen from equation (1) that when carbonic oxide oxidises iron, carbon is set free, but carbonic oxide may carburise the oxygen of oxide of iron,

[1] Howe, *Metallurgy of Steel*, p. 118.

forming carbon dioxide. This action is rapid between 400° and 450° C. These reactions are represented by the following equations:

(4) $FeOx + yCO = FeO\overline{x-y} + yCO_2$.

(5) $FeOx + yCO = FeO\overline{x+y} + yC$.

(6) $2CO = C + CO_2$.

Under altered conditions, and especially at higher temperatures, deposited carbon is oxidised by carbon dioxide and iron oxide, thus:

(7) $CO_2 + C = 2CO$.

(8) $FeO\overline{x+y} + yC = FeOx + yCO$.

The action of carbon dioxide begins at 417° C., that of iron oxide at 265°. A mixture of 60 per cent. by volume of carbonic oxide, with 40 per cent. of carbon dioxide, still deposits a little carbon, but with 50 per cent. of carbon dioxide the deposition is completely arrested. It is to the deposition of carbon that we owe much of the carbon of cast iron, and also the removal of the last trace of the initial oxygen.

Dr. Alder Wright investigated the chemical changes in the blast furnace, which may be expressed by the following equations:

(1) $Fe_2O_3 + CO = 2FeO + CO_2$

(2) $Fe_2O_3 + 3CO = 2Fe + 3CO_2$

(3) $2Fe + 3CO_2 = Fe_2O_3 + 3CO$

(4) $2FeO + CO_2 = Fe_2O_3 + CO$

(5) $2Fe + 3CO = Fe_2O_3 + 3C$

(6) $2FeO + CO = Fe_2O_3 + C$

(7) $2Fe_2O_3 + C = 4FeO + CO_2$

(8) $2Fe_2O_3 + 3C = 4Fe + 3CO_2$

(9) $CO_2 + C = 2CO$

The reactions of carbonic oxide in the blast furnace afford examples of the influence of physical conditions in determining the nature of chemical action. Thus the reduction of oxide of iron by the furnace gases is an example of the influence of mass, since, with a definite proportion of carbonic oxide, no reduction occurs, and with still less of carbonic oxide and a greater relative proportion of carbon dioxide the gases are oxidising in their tendency. Sir Lothian Bell has shown that the rates of carbon deposition in the lower part of the furnace, and of reduction in the upper part, are increased or diminished with the speed with which the carbonic oxide passes through the furnace. This is the influence of mass. Temperature also plays an important part, and with a high temperature carbon dioxide is dissociated, which prevents carbonic oxide completing the reduction of oxide of iron. The silica and other non-metallic oxides are not reduced by carbonic oxide, but by solid carbon at a temperature almost sufficient to melt metallic iron, that is, therefore, in the lower part of the furnace.

The effect of moisture on the blast varies with the condition of the atmosphere. The action of water vapour on hot coke is as follows:

$$H_2O + C = CO + H_2.$$

This is accompanied by an enormous absorption of heat and a corresponding reduction of the temperature of the hearth. The influence of moisture is more marked in cold-blast furnaces than in hot-blast furnaces, and leads to irregularities when the moisture is excessive. It has been proposed to desiccate the blast with a view to decreased fuel consumption and increased production.

Thermal Changes.—Some of the reactions in the blast furnace are exothermic, that is, they produce heat by chemical

action, while in others the reverse is the case, and external heat is therefore required, these are termed endothermic. In[1] the blast furnace there is such external heat, which acts in two ways: (1) By "depolymerising," that is, simplifying the atomic constitution of the carbon, which can then combine with carbon dioxide to form carbonic oxide, thus:

$$CO_2 + C = 2CO$$

with the evolution of more heat than for carbon in its normal condition; (2) by dissociating the carbon dioxide, thus setting free oxygen, which is then in the most suitable condition for combining with carbon to form carbonic oxide. The following equations with the thermal values attached will show the + or − quantities of heat:

$$\underset{199{\cdot}4}{Fe_2O_3} + \underset{3\times 29}{3CO} = \underset{3\times 97 = +4{\cdot}6.}{2Fe + 3CO_2}.$$

The above reaction is therefore exothermic. Again,

$$\underset{2\times 199{\cdot}4}{2Fe_2O_3} + 3C = \underset{3\times 97 = -107{\cdot}8.}{4Fe + 3CO_2}.$$

This is therefore strongly endothermic, and reduction of oxide of iron by carbon seems to be impossible. But the calorific power of carbon varies with its mode of aggregation. In the diamond form it evolves 94 large calories in burning to carbon dioxide, while in the form of charcoal it yields 97 large calories. It may be that the heat of the furnace depolymerises the carbon, and if it is brought to such a molecular condition that the heat of formation of carbon dioxide is 136, instead of 97, then the reaction would be an exothermic one. This is on the assumption that the carbon is burnt as gaseous carbon. We have as yet no knowledge of the molecular form of the liberated iron.

[1] *Introduction to Metallurgy*, by Roberts-Austen, p. 301.

Now, by the equations given on a previous page, it will be seen that metallic iron can decompose carbon dioxide, thus :

$$\underset{97}{Fe} + \underset{}{CO_2} = \underset{66{\cdot}4}{FeO} + \underset{29}{CO} = -1{\cdot}6$$

and by comparing this equation with that in which Fe_2O_3 is reduced by CO, we see the difference is not very great, and in such a case an inverse reaction may readily be brought about by comparatively slight variations in the external conditions.

The reduction of oxide of iron takes place at comparatively low temperatures in the upper part of the furnace. In the middle portion the iron-reducing tendencies are almost balanced by the iron-oxidising tendencies, while the carbon-depositing tendencies are equalled by the carbon-oxidising ones. Here, reduction only takes place slowly, the chief influence on the charge in this region being an increase of temperature. In the lower portions of the furnace the residual iron oxide is reduced by carbonaceous bodies, such as potassium cyanide. There are therefore two principal centres of heat generation, one in the upper part, small in amount, due to the reduction of oxide of iron by carbonic oxide ; the other in the hearth, due to the combustion of carbon by the oxygen of the blast. All the other reactions are endothermic, such as the reduction of phosphorus, silicon, and the formation of slags, etc.

Alkaline cyanides gradually accumulate in the lower part of a blast furnace, and exert a powerful reducing action on oxides. They are probably formed by the metallic vapours of alkaline metals coming in contact with carbon and nitrogen and forming cyanides, which take up oxygen from the oxide of iron, and thus reduce the metal.

The changes occurring in cold-blast charcoal furnaces are different from those above described for hot blast coke

furnaces, for the charge will pass a considerable distance down the furnace before reduction commences. The ore appears to pass from ferric to magnetic oxide, then to ferrous oxide, before being reduced to the metallic state. So that while in coke furnaces reduction takes place in the upper part by the action of carbonic oxide at a low temperature, the reduction in a charcoal furnace takes place in the middle of the furnace at a comparatively high temperature.

The maximum temperature in a blast-furnace is in front of the twyers, being nearer with hot-blast than with cold-blast. The temperature of the zone of fusion is determined by the degree of fusibility of the slag. The temperature of the upper part of a furnace is determined by the temperature of the blast and the nature of the fuel. In coke furnaces, while the use of hot-blast causes the upper part of the furnace to be cooler, and the gases leave at about 200° C.; in charcoal furnaces, where the zone of reduction is lower, the upper parts are much cooler, and the gases may not be above 100° C. on their escape.

REDUCTION OF ELEMENTS OTHER THAN IRON.

Silicon.—This element is not reduced by carbonic oxide or carbon alone, except in the presence of iron or similar metals. Usually only a very small proportion of the silicon present is reduced. To get highly silicated irons, we require very high temperatures, and highly silicious ores. The blast must be very hot, and worked at high pressure. The burden of ore must be light in proportion to the fuel. Silicon pig iron usually contains about 10 per cent. silicon.

Phosphorus.—This element chiefly occurs as calcium phosphate, which is not reduced by carbon unless sufficient

silica is present to combine with the lime. As this forms a neutral or an acid slag, the phosphoric acid cannot enter the slag, and is therefore reduced, and phosphorus passes into the iron. If, however, a rich scouring slag is present, some of the phosphoric acid unites with the oxide of iron in the slag.

Manganese.—The manganese present in iron ores is only partially reduced in the blast-furnace, and the remainder passes into the slag as oxide of manganese, MnO. To prevent manganese passing into the slag, the latter must be made basic in character, by using much lime. To produce spiegeleisen, manganiferous ores are mixed with the charge, and to produce rich ferro-manganese, the charge of ore must consist chiefly of rich manganese ores. In each case a very high temperature is necessary, a basic slag must be produced, and a light burden of ore employed.

Sulphur.—This element is usually only present in iron ores in small quantities, and not more than 5 per cent. of this passes into the iron, the remainder being chiefly found in the slag. The high temperature of a blast-furnace tends to prevent the iron from absorbing sulphur. If the slag is basic, the sulphur more readily passes into it. Manganese, silicon, and perhaps other elements, tend to prevent the sulphur uniting with the iron. Pig iron may be desulphurised by lime or ferro-manganese.

NATURE OF FUEL USED IN BLAST FURNACE.

The Fuel used in a blast furnace is either charcoal, peat, coke, or raw coal. Charcoal is only used in small furnaces, on account of expense, but it is highly advantageous when very pure iron is required, owing to its freedom from sulphur and other impurities. Peat is only used in remote districts where other fuel is not available.

The value of coke for blast furnace work is largely dependent upon its comparative freedom from sulphur and ash. The coke must be sufficiently hard and dense to resist the great pressure of materials it has to sustain in large furnaces; on the other hand, it must be sufficiently porous to allow free passage for the ascending gases. It works best with a very hot blast. Anthracite, notwithstanding its comparative purity, is very dense, and only permeable with difficulty; it is also very liable to decrepitate into small fragments, which retard the draught. In South Wales, where this fuel is used, it is necessary to work with an open tymp, so as to be able to clear out the small particles of anthracite from the hearth. Raw coal is very largely used, both alone and in admixture with coke, which is probably the most advantageous method. The coal employed should be of the non-caking variety; hence we find raw coal in use in the West of Scotland, Staffordshire, and Derbyshire.

Coke.—The average consumption of coke per ton of iron made is from 19 to 28 cwts., according to the kind of ore to be smelted. In Cleveland it varies from 20 to 24 cwts. Haematite requires 19 to 20 cwts.

The coke is made in piles, beehive and other ovens, such as the Carvé, Semet-Solvay, etc. Good coke contains about 90 per cent. carbon; the residue being ash, sulphur compounds, and moisture. The quantity of ash is important, as it requires flux to remove it, and adds to the quantity of slag produced. As even good coke contains about 1 per cent. of sulphur, it introduces that element into the charge, and consequently increases the amount of sulphur in the iron. Gas coke is sometimes used in admixture with other fuels; it contains 1·5 to 2 per cent. of sulphur, besides being soft and friable. The coke used in blast furnaces varies in composition from 85 to 92 per cent. of carbon, 0·5 to

1·0 of volatile matter, 6 to 14 of ash, and sulphur from 0·5 to 1·8 per cent.

Coal.—The non-caking variety is generally used. It is customary to use a mixture of coke and coal. An average composition of the coal used for the blast furnace may be: Carbon (fixed), 62 per cent.; volatile matter, 32 per cent.; ash, 5 per cent.; and sulphur, 0·7 per cent. When coal is used alone, about 35 to 40 cwts. are required per ton of pig iron made. Scotch splint coal contains 50 to 55 per cent. of fixed carbon; sulphur, from 0·7 to 1·0; volatile matter, from 38 to 42; and ash, from 3 to 5 per cent.

Anthracite.—This highly-carbonised fuel is largely used for blast furnace work in South Wales and in the United States. It is a kind of natural coke, and burns very slowly. Although its carbon content is equal to that of coke, more anthracite than coke is required to produce a ton of pig iron. Owing to its tendency to splinter and crumble, it is usual to remove the finer portions by screening before introducing it into the blast furnace. Its use necessitates a blast with a pressure of 9 to 12 lbs. per square inch. About 24 cwts. of anthracite are required for the production of one ton of pig iron. The carbon varies from 90 to 94 per cent.; the sulphur, from 0·6 to 1·5; the hydrogen, from 1·5 to 4·0; nitrogen and oxygen, from 2·0 to 3·5; and ash, from 1 to 7 per cent.

Charcoal.—This is the purest kind of fuel, being practically free from sulphur, and containing 1 to 2 per cent. of ash. Usually 16 to 17 cwts are required in charcoal blast furnaces for the production of one ton of pig iron. Cold blast, or blast not exceeding 200° C. is used, because of the lower density and ready combustibility of charcoal.

Action of Carbon in Blast Furnaces.—The effect of the blast on the carbon of the fuel is to produce carbonic

oxide, which is the chief reducing agent according to the formula: $Fe_2O_3 + 3CO = 3CO_2 + 2Fe$. If the reduction were possible by the above reaction alone 84 parts by weight of carbonic oxide would produce 112 parts by weight of iron. But the carbon dioxide formed is an oxidising agent and therefore acts in opposition to the monoxide, so that a certain excess of the monoxide is necessary to neutralise it. The following equation therefore more nearly represents the reaction:

$$Fe_2O_3 + 9CO = 2Fe + 3CO_2 + 6CO.$$

According to this equation 20 cwts. of iron will be produced from $\frac{20 \times 160}{112} = 28{\cdot}6$ cwts. of ferric oxide. And the oxygen removed from the 20 cwts. of iron will be 8·6 cwts. Now in the above nine molecules of CO there are 108 parts of carbon, which remove three atoms of oxygen from the Fe_2O_3, therefore $\frac{8{\cdot}6 \times 108}{48} = 19{\cdot}35$ cwts. of carbon are required for the reduction of the 20 cwts. of iron. But it has been shown that oxide of iron is only partly reduced by carbonic oxide in the blast furnace and that a portion is reduced by solid carbon. Besides this there is the quantity of carbonic oxide carried out in the waste gases, and the quantity of carbon absorbed in the reduction of other oxides as well as that taken up by the iron to carburise it.

Other operations, requiring heat only, are the expulsion of water from hydrates and moist ores, of carbon dioxide from limestone, of the removal of volatile matter from coal, and the fusion of metal and slag. According to Sir Lothian Bell,[1] the relative calorific importance of these factors may be estimated as follows in smelting Cleveland

[1] *Manufacture of Iron and Steel*, p. 95.

iron-stone for No. 3 pig-iron. The figures are expressed in 20 cwts. and the corresponding heat units in degrees centigrade:

	Weight in Cwts.	Heat Units per Cwt.	Total Heat Units.
Reduction of Fe_2O_3 to Fe,	18·60	1780	33,108
Carburising reduced iron,	0·60	2400	1440
Evaporation of water in coke,	0·58	513	313
Reduction of P_2O_5, SO_3, and SiO_2,	—	—	3500
Fusion of pig iron,	20·00	330	6600
Calcination of flux,	11·00	370	4070
Reduction of CO_2 of flux to CO,	1·32C	3200	4224
Decomposition of water in blast,	0·05H	34,000	1700
Fusion of slags,	27·92	550	15,366
			70,321
Transmission through walls of furnace,			3600
Carried off in twyer water,			1800
Expansion of blast, transmitted to ground, etc.,			3389
			79,110
Carried off by gases,			7900
Total heat requirements per 20 cwts.,			87,010

The heat required for these operations is derived from the combustion of the fuel and the heat of the hot blast. As regards the former it is not possible to oxidise the carbon of the fuel beyond the ratio $\frac{2CO}{CO_2}$ in the waste gases, under which condition the heat developed is $\frac{8000}{3}+\frac{2\times 2403}{3}$, or 4269 units per unit of carbon; or, assuming the fuel to contain 10 per cent. of volatile and non-combustible matter = 3842 units per unit of coke. If the blast is heated to 540° C., the heat may be estimated at 12,000 units to be furnished by the combustion of the coke, which, on the estimate given above, corresponds to

19·53 cwts. This means that 86 per cent. of the heat is furnished by the fuel and 14 per cent. by the blast.

The heat of the blast is furnished by the combustion of the waste gases, which furnish a further amount of heat for raising steam, estimated at 28,000 units, while about 11,000 units are available for other purposes. The duty of the fuel used may be summarised as follows:

Heat generated by complete combustion of 19 units of carbon, burnt to CO_2 (19 + 8080),		153,520
Useful heat—		
Furnace work as in previous table,	70,321	
Heat in steam generated,	28,118	
Heat in unutilised waste gases,	10,837	
Heat in twyer water,	1,800	
		111,176
Waste,		42,344

The thermal efficiency is about 73 per cent., or considerably higher than that for any other industrial process for which very high temperatures are required.

Of the 87,000 units of heat required in smelting the Cleveland ore previously referred to, about one sixth is required for the slag. It is evident then that any furnace working on rich ores, where the slag produced is low in quantity, will effect a considerable saving of heat, since the absorption of heat by the slag is much less, and less fuel will be required per ton of pig-iron produced. This difference will be greater the purer the fuel used, for if charcoal is used instead of coke, less slag will be required, as in coke there is more ash and always sulphur, and to keep this out of the iron more slag is required.

In charcoal furnaces, using cold blast, the fuel consumption per ton of iron produced is about two thirds that of the hot-blast coke furnace. The carbon is more completely oxidised and as the reduction occurs lower

down the furnace the top of the furnace is cooler and the gases leave at a lower temperature. The carbon dioxide, produced by the reduction of the oxide of iron, being low down in the furnace, is converted to carbonic oxide by the carbon of the fuel and acts on fresh portions of the oxide of iron. Probably in charcoal furnaces the oxide of iron is largely reduced by solid carbon. In such furnaces, rich ore is generally used, hence less flux is required and less slag produced. Theoretically by the equation

$$Fe_2O_3 + 3C = 2Fe + 3CO,$$

1 ton of iron is reduced by $6\frac{1}{2}$ cwts. of carbon.[1]

FLUXES AND SLAGS OF IRON SMELTING.

The Fluxes employed in iron smelting vary with the nature of the ore to be treated. In some rare cases the ores are self-fluxing, containing basic and acid constituents in the requisite proportion to form slag. This may also be effected by using a mixture of ores of dissimilar composition, such as siliceous and calcareous haematites, or both, with clay-ironstone. More generally a non-ferruginous flux is added, and although it increases the weight of material to be operated upon, it is more easily obtained.

For ironstone containing clay, which is very frequently the case, limestone is the flux used. Rich haematites, such as those of Cumberland and Lancashire, require clay as well as limestone. Of late years, a brown haematite containing much free alumina called "Belfast Aluminous-Ore" has been used in preference to clay. Some smelters recommend the use of quick lime instead of limestone, and thus effect an economy of fuel, since the absorption of

[1] Turner, *Metallurgy of Iron*, p. 173, and *Journ. Iron and Steel Inst.*, No. 2, 1893, pp. 219-284.

heat by the expulsion of carbon dioxide in the case of the raw carbonate, as well as the carbon removed by the conversion of carbon dioxide into carbonic oxide, is avoided; but it is necessary to use the lime soon after burning, otherwise it takes up carbon dioxide and moisture again from the air. When the ore is a carbonate, containing metals in the protoxide condition, the flux required is silica, added in quantity sufficient to form a silicate in which the oxygen of the acid would be equal to the oxygen in the base, thus: ($2MO \cdot SiO_2$).

Calculation of Fluxes.—The quantity of flux required for a given gangue will vary with the nature, as well as with the amount, of gangue to be removed. Take the case of a blast furnace slag, which is a monosilicate, containing $2Al_2O_3$, $3SiO_2 + 2MO$, SiO_2 where M represents lime and magnesia, and suppose the ore to be smelted is oxide of iron, associated with clay containing an excess of silica. Now the gangue of the ore and the ash of the fuel may contain for example 8 per cent. of alumina, 4 per cent. of magnesia, 7 per cent. of lime, and 20 per cent. of silica.

$$2Al_2O_3 \cdot 3SiO_2 = 204 + 180 = 384$$
$$2MgO \cdot SiO_2 = 80 + 60 = 140$$
$$2CaO \cdot SiO_2 = 112 + 60 = 172$$

Now 204 Al_2O_3 requires 180 SiO_2 ∴ 8 will require 7·06
„ 80 MgO „ 60 „ ∴ 4 „ „ 3·00
„ 112 CaO „ 60 „ ∴ 7 „ „ 3·75
13·81

13·81 parts of silica are therefore satisfied, leaving 6·19 to be fluxed off. If lime be the flux, as is usual, then by the above proportion 60 parts of SiO_2 require 112 parts of CaO, therefore 6·19 will require 11·55 parts of CaO to be

added. The following graphic method of determining the proportion of flux to be added is given by Balling (Fig. 32). The dark line represents the proportion of silica to alumina as given in the above formula; and the thin lines the proportion of silica to lime and the proportion of silica to magnesia. To determine the amounts given in the above calculation, draw lines parallel to the given lines from the

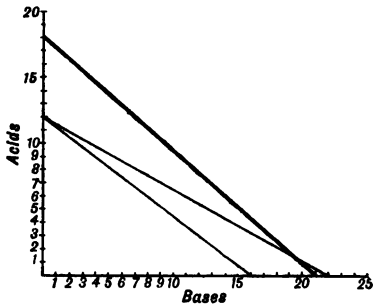


FIG. 32.

acid line to the base line for each metallic oxide, and the reverse if the silica is required, and where they cut the horizontal and vertical line respectively the amount of base or acid to be added as a flux will be indicated. Thus, for alumina, a line drawn from 8 on the base parallel to the dark line will cut the vertical at 7·06; or a line from 6·19 on the vertical drawn parallel to the upper thin line will cut the base at 11·55, which is the amount of lime required in the above calculation.

If ores contain only oxides of iron, manganese, and silica, limestone alone is hardly sufficient; argillaceous ores should be added, such as Belfast aluminous ore, or Bauxite. In the Cleveland district it is the practice to add Cleveland slag. Calcareous ores, as before stated, require mixing with ores containing alumina and silica.

Balling has also constructed the following table for easily calculating the necessary amounts of base or acid to yield a suitable slag:

One Part by Weight of Silica requires—	Parts by Weight of Bases.	One Part by Weight of Base requires—	Parts by Weight of Silica.
For Monosilicates—		For Monosilicates—	
Lime, - - -	1·86	Lime, - - -	0·535
Magnesia, - -	1·33	Magnesia, - -	0·750
Alumina, - -	1·14	Alumina, - -	0·873
Ferrous oxide, -	2·40	Ferrous oxide, -	0·416
Manganous oxide, -	2·36	Manganous oxide, -	0·422
For Bisilicates—		For Bisilicates—	
Lime, - - -	0·93	Lime, - - -	1·070
Magnesia, - -	0·66	Magnesia, - -	1·500
Alumina, - -	0·57	Alumina, - -	1·747
Ferrous oxide, -	1·20	Ferrous oxide, -	0·833
Manganous oxide, -	1·18	Manganous oxide, -	0·845
For Sesquisilicates—		For Sesquisilicates—	
Lime, - - -	1·24	Lime, - - -	0·803
Magnesia, - -	0·88	Magnesia, - -	1·125
Alumina, - -	0·76	Alumina, - -	1·310
Ferrous oxide, -	1·60	Ferrous oxide, -	0·625
Manganous oxide, -	1·57	Manganous oxide, -	0·633

Utilisation of Blast Furnace Slag.—The harder kinds, if not too glassy, are used for mending roads, for levelling waste lands, for building break-waters, and as ballast. In the form of large blocks slag is used for road making.

It is used for building purposes when suitable. For this purpose it is moulded into bricks, which are kept at a strong heat for several hours in a closed space in order to devitrify them and make them harder. Good bricks are made of granulated slag mixed with lime. If not too acid it may be burnt in a state of powder with lime and yields a good hydraulic cement. The following are analyses of slags used for this purpose:[1]

[1] *Intro. to Metall.*, Roberts-Austen, p. 241.

	Middlesborough.	Bilbao.	Saulines, France.	Chrindez, Switzerland.	Hartzburg, Germany.	Belgium.
Lime, - - -	32·75	47·30	47·20	45·11	48·59	44·75
Silica, - - -	30·00	32·90	31·65	26·88	30·72	32·51
Alumina, - -	28·00	13·25	17·00	24·12	16·40	13·91
Ferrous oxide, -	0·75	0·46	0·65	0·44	0·43	0·48
Magnesia, - -	5·25	1·37	1·36	1·09	1·28	2·20
Calcium sulphide,	1·90	3·42	—	1·86	2·16	4·90
Manganese oxide,	0·60	1·13	0·85	0·50	—	0·60
Residue, - -	0·75	0·17	1·29	—	0·42	0·65

Slag wool is made from blast furnace slag by blowing steam on to a thin stream of the slag in such a way that the steam only encounters half of the stream. It is light and fire-proof, and used for covering steam pipes, etc.

CHAPTER XI.

BLAST FURNACE.

AN English blast furnace of the old type (Fig. 33) was a very massive structure of stonework or brickwork, usually circular in cross section in the interior, which consisted of a shaft approaching in sectional elevation to that of two truncated cones joined at their bases; the upper and more acute one being termed the "body," which was surmounted by a chimney containing one or more openings for the purpose of charging; the lower cone forming the "boshes." This lower cone was sometimes continued to the ground level, but more often the furnace was enlarged, forming the "hearth," in which the molten iron collected, three sides being continued to the bottom, and the other left open for means of access. The hearth was supported on a mass of masonry, with channels for the escape of moisture. The foundations were traversed by arched galleries in order to keep the whole building dry. One of the objects in the construction was to keep the heat as much as possible in

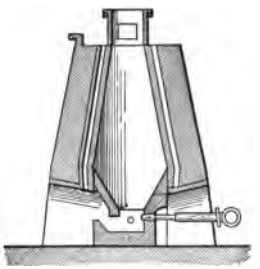


FIG. 33.

that part where it was required, and to diminish loss of heat by radiation. The interior was lined with firebrick, and the outer part was built of rough sandstone or ordinary brickwork, the two layers being separated by a space filled with sand or slag. The dimensions varied in England from 9 to 20 feet in diameter, and 30 to 45 feet in height.

The modern blast furnace is an elongated barrel-shaped structure, the height being four to five times that of the greatest width. The body is formed of wrought-iron plates, ½ inch thick, riveted together, and within which is built the outer casing of ordinary masonry, the inside being lined with firebrick, about 18 inches thick, while in some cases between the two layers of brickwork is a small space filled with sand to allow for expansion and contraction. The body or stack is supported on a cast-iron ring resting on iron pillars, and the lower part, from the top of the columns to the hearth, is also cased with iron, and in some cases with water blocks. The hearth is independent of the masonry of the stack, and is built in after the stack is completed. It requires to be made of very refractory material of considerable thickness, having to withstand a very great heat in addition to the corrosive action of the molten slags.

The hearth is perforated with three to six holes for the introduction of twyers, which convey the blast of air into the furnace. On the front or working side the hearth was formerly extended outwards for a short distance, forming a rectangular cavity known as the fore-hearth, which was bounded in front by a refractory stone termed the dam-stone. The arch covering this was called the tymp-arch. The tymp was made either of a block of refractory stone or of a hollow cast-iron box built in the masonry, and through this box a current of water constantly circulated in order to keep it cool.

In Fig. 34, *A* is the charging gallery, *B* is the cup and cone arrangement for charging, *C* the throat, *D* the body, *EE* the boshes, *F* the blast main, *G* the iron ring, and *HH* the pillars supporting the body, *I* the hearth, *KK* the twyers. The dam was formed of firebrick, and carried up to the twyer level, a semicircular notch in the top edge serving as a passage for the slag. The tap hole for the molten iron is a narrow slit through the bottom of the hearth or crucible, and *N* is the opening for conveying into the down-take pipe the waste gases, which are utilised for heating the blast, boilers, etc.

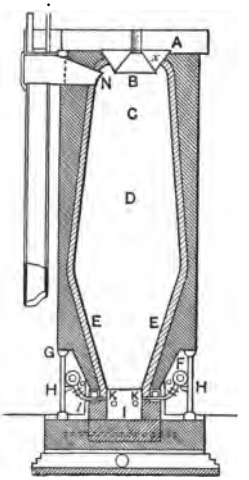


FIG. 34.

The charge is tipped into the cup or hopper *x*, and allowed to fall into the furnace by lowering the cone *B*, which acts very advantageously in distributing the charge over the surface of the materials already in the furnace.

The great increase in the height and capacity of modern blast furnaces is one of the chief features of present practice. Forty years ago the capacity of the largest furnaces did not exceed 12,000 cubic feet, and very often not more than 6000 cubic feet. The height was about 50 to 60 feet, as compared with 80 to 100 feet at the present time. The diameter of the boshes was 16 to 20 feet, now it is 25 to 30 feet, with a furnace capacity of 30,000 cubic feet or more. The determination of the capacity of a furnace will depend on the nature of the ore and fuel to be used. The increase of capacity of the modern blast furnace has resulted not only in a much greater output, but also in

greater economy, as the quantity of fuel required per ton of iron is less.

Fig. 35[1] shows a plant of three blast furnaces with the necessary accessory apparatus. The three furnaces are each 85 feet high from hearth to platform, 28 feet at the boshes, and has a capacity of 30,000 cubic feet. The blast enters the furnace through 6 twyers at a temperature of 670° C. The diameter of the charging bell is 13 feet. There are 2 Cowper regenerative stoves for each furnace, each 23 feet diameter and 54 feet high. These are changed every hour from gas to blast. All the stoves open into one common main before entering the furnace, each being fitted with a valve, so that each can be worked independently if desired. Fitted to each stove are Lister's instantaneous opening valves, by means of which the blast is emptied from each stove suddenly and with great velocity, every time the stove is changed from blast to gas. This clears the stove of dust. One brick chimney is common to all the stoves, and the burnt gas is drawn by it through a flue, which is connected to each stove in succession.

The blowing engines are four in number, having 78-inch diameter blowing cylinders, and 40-inch steam cylinders, so as to allow of having one off for repairs when necessary. They are capable of blowing at a pressure of 9 to 10 lbs. per square inch. A tank covers the engine-house for supplying water to the twyers. The 14 boilers supply the necessary steam for the hoists, pumps, kilns, and furnaces.

There are five calcining kilns, each 26 feet in diameter and 40 feet high; they also carry the girders which form a double roadway for the conveyance of trucks carrying ore, and necessary fuel. The trucks are lifted to the top of the calciners by means of a direct-acting overhead steam-lift.

[1] Samuelson, *Jour. Iron and Steel Inst.*, No. 1, 1887.

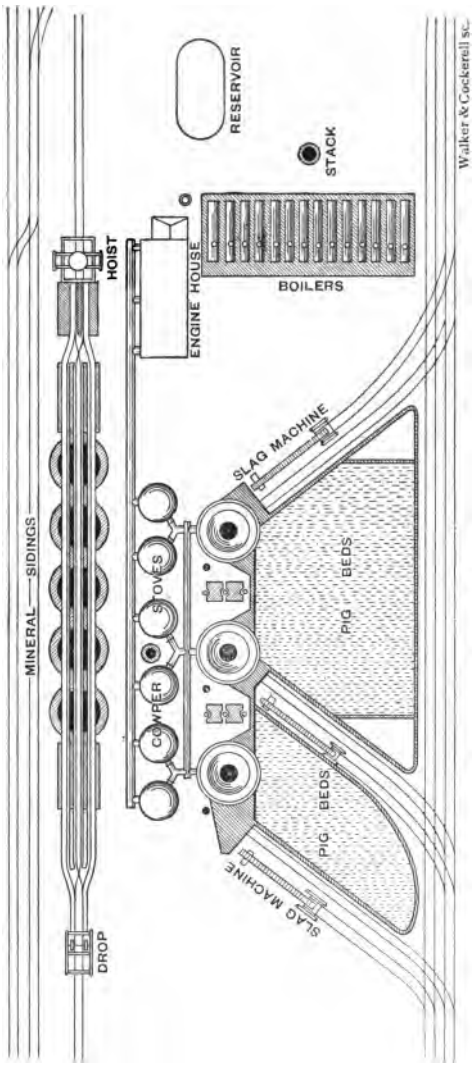

RESERVOIR
STACK
BOILERS
ENGINE HOUSE
HOIST
MINERAL — SIDINGS
DROP
COWPER
STOVES
SLAG MACHINE
PIG BEDS
PIG BEDS
SLAG MACHINE
Walker & Cockerell sc.

FIG. 35.

The molten slag is run from the furnace through a bronze tube about 1' inch in diameter, and conducted down a trough into pans fixed on an endless chain of bar links. This chain passes over two 4-feet pulleys, placed 45 feet apart. The outer pulley is fixed at such an elevation

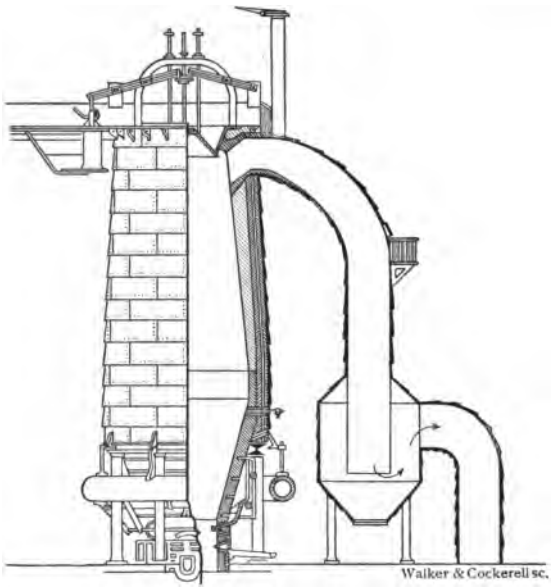


FIG. 36.

that the trucks can be run underneath. The slag is emptied into trucks which convey it away. The cost of such a plant is £74,000.

Fig. 36 represents a modern blast furnace as used in some American works. The general arrangement of the blast furnace has been already described. It is about 85 feet high, 23 feet wide in the greatest diameter, and 11 feet diameter at the hearth. The hearth is protected by water-cooled plates, and in the boshes are four rows of bronze

cooling plates, eight plates forming the circle, and each plate having two water courses. Cast iron cooling plates are also placed between the twyers, the number of the latter being seven, each 6 inches in diameter. The cubical capacity is about 20,000 cubic feet. The charging bell is 12 feet, and the throat 15½ feet in diameter. The volume of air blown in is 24,000 cubic feet per minute. The temperature of the blast is 650° C., and the average pressure 8 lbs. per square inch. The ores are generally richer than our ironstone, so that only 10 cwts. of limestone are required for flux per ton of iron produced, and this amount of iron is produced with 17 cwts. of coke. The output of iron per furnace is about 2000 tons per week. The following comparison between a typical English and a typical American blast furnace will show the different conditions in each case:

	Cleveland.	Pittsburg.
Cubical contents,	25,500 ft.	18,200 ft.
Temperature of blast,	704°	593°
Coke, per ton of ore,	19·99 cwts.	16·8 cwts.
Limestone,	11·00 ,,	9·0 ,,
Ore,	48·00 ,,	32·3 ,,
Weight of blast per ton of iron,	87·15 ,,	71·2 ,,
Weight of gases,	119·50 ,,	100·1 ,,
Temperature of gases,	250° C.	171° C.
Tons of iron for 1000 cubic feet space of furnace per week,	21·57	128·0
Slag per ton of iron,	28·00 cwts.	10·7 cwts.
Calories produced per ton of iron,	88,577	69,569

It will be observed from the above figures that the English furnace has much the greater capacity, the temperature of the blast is higher and the calories of heat required per ton of iron are more, therefore the fuel used per ton of ore is greater, the blast is hotter, the waste gases

escape at a much higher temperature, the flux required is greater and the slag produced is greater. The great reducing energy of the American furnace, with its high grade ore and rapid working, yields six times as much iron per cubic foot of space as the English furnace.

As an example of a modern American blast furnace the Lorrain plant may be taken. It consists of two furnaces, 100 feet high, 22 feet in diameter at the boshes, and 14 feet in the hearth. The hearth jacket is carried much deeper than usual, and there are two rings of bronze cooling plates below the twyers, ten rings above them, and then a further three rings of cast iron cooling plates, or 277 bronze and 48 cast iron plates in all. The stack lines are protected by twelve rings of cast iron segments built into the brickwork. The furnace is blown through sixteen 6-inch twyers. The gases are led through two downcomers, 63 inches in internal diameter, into a dust catcher, and may be further purified in washers. Each furnace has four stoves, the heating surface in each being 34,000 square feet, and two blowing engines. These engines have steam cylinders 44 and 84 inches, and air or blowing cylinders 84 inches in diameter, with a common stroke of 44 inches. The usual pressure of the blast is 14 lbs. An endless belt pig-casting machine is used, and to prevent the pig iron sticking to the moulds they are smoked instead of being washed with clay. Ladle trucks, each holding 15 tons, take the iron from the furnace to the casting machine. The slag ladles have a capacity of 200 cubic feet, and have renewable cast iron linings. Each furnace is tapped six times daily, and a pneumatic tapping gun is used to stop the tap hole. A tilting metal-mixer, holding 300 tons, is used to mix the charges of iron from the blast furnace when such metal is to be used for conversion into steel.[1]

[1] Johnson, *Engineering News*, Vol. xlv., p. 248.

Pig-bed.—This consists of a sand bed with parallel grooves of a semi-cylindrical section, generally with their long axes towards the tap-hole, while the top ends of these furrows in

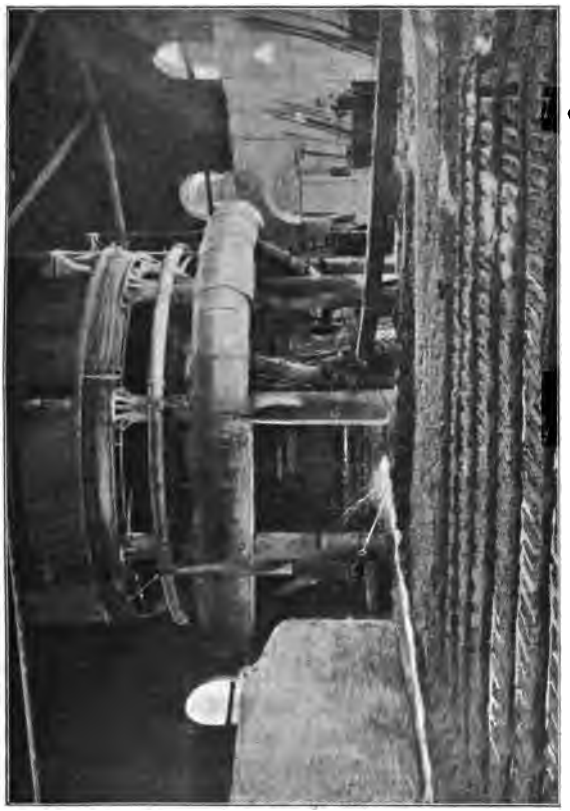


FIG. 87.

each row are connected with a common channel running at right angles to them, and known as the sow or feeder. These feeders are themselves put in connection with the

main feeder or channel, leading from the tap-hole to the lower end of the pig-bed. In order to tap the furnace the blast is turned off and the tap-hole opened by means of an iron rod, when the iron flows along the main channel to the lower row of moulds, and when these are sufficiently filled, communication between the transverse channel or sow and the main channel is made with a spade, whereupon the metal takes the next channel nearer the furnace, and so on until the whole of the pig moulds are filled. When the iron has sufficiently cooled, the pigs are broken from the runners and removed by hand labour.

In some works the moulding is done by mechanical means, so that the pigs are of uniform size and equidistant from each other, and are cast in groups of thirty or more. When the metal is cold, an overhead crane picks up the group and carries it down an incline to a pig breaker. In America grapplers are used, suspended from trolleys running on a traveller, which spans the pig-bed. A powerful electro magnet, suspended from a crane, is also employed, which can be lowered or raised at will, and by stopping the current the iron is dropped. The usual method of breaking pigs is by manual labour, by lifting each one to a certain height and allowing it to fall on an iron ball. Pig breaking machines are now coming into use. Fig. 37 shows the lower part of a blast furnace with metal being run into the pig-bed.

Casting Machines.—Pig iron casting machines are of various patterns. Ramsay's machine is of the rotary table type. One of the special features is the pouring device, which consists of a horizontal drum with radial holes mounted over the moulds and driven so that the molten metal is delivered into the moulds and cannot flow on to their edges. Tapping devices are also arranged to knock the bottom of the overturned mould, so as to free the pig.

The enormous and arduous manual labour involved in the removal of hot pig iron from the usual sand moulds has led many ironmasters to consider the advisability of substituting mechanical arrangements for hand labour. Another consideration is the disadvantage of having so much sand adhering to the pigs, which is not only objectionable for foundry purposes, but also for Bessemer and open-hearth methods of dealing with pig iron. If then the troubles of manual labour can be dispensed with, and, at the same time, pigs can be obtained free from sand at a reasonable price, a great advantage will be gained. Mr. Wainford claims to have solved the problem in the use of his casting machine. But casting into iron moulds chills the metal, and produces a different fracture, and as many founders rely upon fracture for judging of the quality of the iron suitable for their purpose, a difficulty arises as to the disposal of the pig iron cast in chills. If chemical analysis were universally resorted to, this difficulty would disappear. Great strides have been made in this respect in America, and probably other countries will have to follow suit. Mr. Wainford endeavours in his method to produce sandless pigs with as good a fracture as those cast in sand in the usual pig-bed. The iron from the blast furnace is run into a 15-ton tilting ladle, placed on a trolley, which runs on a railway track to a series of 40 moulds, and underneath the moulds are waggons, also on rails, for receiving the contents of the moulds after the iron has solidified. The moulds are constructed in a light corrugated form and placed in semicircular casings, leaving a space between the moulds and the casings, in which is placed non-conducting material. These casings are fitted with trunnions on which they revolve for discharging. The iron solidifies in about 10 minutes, and can then be tilted over. The moulds never fall below 450° C., and by

keeping them hot in this way better fracture results are obtained.

Form and Interior Dimensions.—The descent of the materials must, in all cases, be sufficiently slow for the reducing action of the gas and carbon to penetrate to the centre of each fragment before it reaches the region of fusion, and, as a rule, the furnace is built smaller in proportion to the ease with which the various oxides are reduced.

The horizontal section given to the hearth must vary according to the pressure of the blast and the porosity of the materials employed in the furnace. When hard coke is used and the ore is in large pieces, a longer time is required for the gas to penetrate to the centre of each lump, and a greater pressure is then needed. But this tends to produce a higher temperature, and, consequently, greater reducing energy, which necessarily makes the metal more impure. The height of the furnace should be limited when the fuel is friable, such as anthracite, and when the ore is in small pieces, for if the charge is too compact the gas can only circulate with difficulty. Moreover, in a mass of different materials, descending gradually, the effect of the difference of density becomes greater as the height of the furnace is greater; the heavier pieces of ore tend to descend vertically while the lighter particles of fuel are forced to the sides, which circumstance limits the possible height. The internal shape of a blast furnace should be that of the general form which it tends to assume after some weeks of working. It has been found in practice that, the section has been modified where the heat has been greatest, and that the sharp angles of the hearth and boshes of the older forms were invariably burnt away. The boshes are arranged at an

FIG. 38.

FIG. 39.

angle of about 75° and fairly low in the furnace. When a furnace is working irregularly, which often arises from an accumulation of lime and unreduced ore in the hearth and boshes, it is generally due to scaffolding. Fig. 38 is a section of a furnace showing an excrescence of this kind, given by Mr. R. Howson, who recommends the shape Fig. 39 as the best form for avoiding scaffolds. Greater height may be given to a furnace to increase its capacity, and also to utilise the heat more completely. Combustion should only occur in the neighbourhood of the twyers, and the greater the distance of the upper end of the charge from the zone of combustion, the more perfectly will the heat be extracted from the ascending gases, so that furnaces are now built 80 to 100 feet in height.

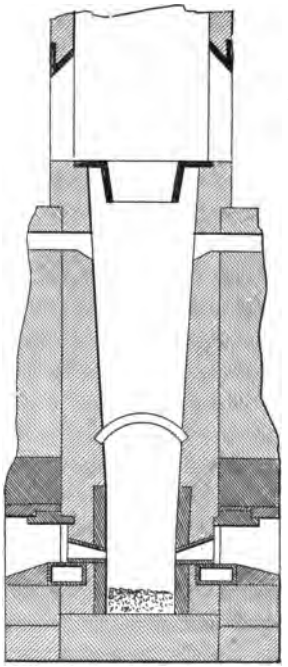


Fig. 40.

The section of most furnaces is round, which economises the heat, and causes it to be more uniformly distributed; but there is always a difficulty in forcing the blast to the centre, since the charges sink more there than at the circumference. This circumstance induced Rachette to adopt an elliptical or oblong section. The large production of 30 tons of grey iron in twenty-four hours in this small furnace is due to the suitable distribution of the blast, and the non-conducting

nature of the walls. Truman states that the charges descend uniformly to the twyers, thus utilising the fuel more completely, and that the smelting is rapid. This furnace (Fig. 40) is oblong or elliptical in shape, being 3 feet wide at the twyers, 7 feet at the throat, and about 30 feet high, with a capacity of 2000 cubic feet. The object of this shape is to keep the ascending gases more to the centre, and to cause a more perfect action on the descending solid materials. The blast is introduced through six or eight twyers, three or four being placed on each of the longer sides of the hearth, thus causing a better distribution of the air.

It is usual to support the fittings at the top of a blast furnace on iron brackets attached to the casing. As the lintel has to support a great weight, it is supported by relieving arches sprung from column to column. In America it is usual to have rolled joists, bent to the circle of the furnace, upon which the lintel-plate rests. Recently furnaces have been built in which the charging platform is supported on staging separate from the furnace. The boshes have also been made separate from the stack.

The hearth of a modern blast furnace is circular in section, 8 to 14 feet in diameter. The larger the diameter of the hearth and the greater the vertical distance between the slag notch and twyers, the greater is the output, as by enlarging the hearth the melting area is increased, and by raising the twyers above the slag level, fusion proceeds without hindrance. The bottom is made of refractory sandstone, which is at first flat, but gradually wears into a hollow, in which a somewhat infusible mass collects, termed a "bear." In consequence of this it is advisable to so arrange the tap-hole that a few inches of liquid is always retained in the hearth. The tap-hole should be on a line mid-way between two twyers, and the same remarks apply to the slag-notch.

Of the disturbances that occur in the working of blast furnaces, the stoppage of the charge during its descent is one of the most frequent. Hanging-up or scaffolding consists of one portion of the charge adhering to the furnace sides and preventing the descent of the remainder, thus leaving the part below comparatively empty. If allowed to continue it will stop the working of the furnace. The furnace during this scaffolding takes a smaller quantity of blast, less slag is formed, the flame at the throat is of a blue or bluish-red colour, and free from smoke and dust. This is remedied by removing one of the twyers, so as to form a hole in the hearth, and increasing the pressure of the blast. This blows out the charge below the choked part, and gradually the material falls, and a passage for the gases is again formed. The cause of scaffolds may be due to bad coke, fine and damp ores, very hot blast, or the accumulation of deposited carbon. It may also be due to the charge beginning to clot and fuse too soon.

The destruction of blast furnace linings is, according to Lurman, due to several causes: 1. By friction and wear, due to contact with the descending charge. 2. By the chemical action of the gases, and of cyanogen and its salts. 3. By the action of sodium chloride contained in the coke. 4. By flaking, due to the deposition of carbon, caused by iron particles reduced from iron pyrites, etc., in the lining material.[1]

Hot-blast.—The use of hot air was first introduced by Neilson at the Clyde Iron Works in 1828, and was soon attended with great economy of fuel, and an increased make of iron. The arrangements for heating the blast are of two kinds—cast-iron pipes, through which the air passes, and heated externally; and chambers of refractory brickwork, constructed on the principle of Siemens' regenerators, which

[1] *Stahl und Eisen*, Vol. xii., p. 114.

are now in more general use. There is some reason to believe that Neilson had originally little conception of the immense value of his invention, or of the important influence it was destined to make on the smelting of iron ore. In 1832 Messrs. Baird, of the Gartsherrie Ironworks, disputed the royalty they agreed to pay the patentee, contending the want of novelty, and that cold blast was preferable. The jury awarded the patentee £11,876 damages, showing how soon the value of the invention was recognised by ironmasters. Heated air is now almost universally employed, and cold blast is, with few exceptions, a thing of the past. The temperature at which the blast can be advantageously used is only limited by the wear of the apparatus, and by the difficulty of keeping the joints tight. As a direct consequence of using hot blast, coal can be employed in the blast furnace instead of coke, as the coal is practically converted into coke in the upper part of the furnace. All kinds of coal are not suitable, as caking coal tends to agglomerate the materials and prevent the proper intermixture of the gases. The splint coal of Scotland, the coal of Staffordshire, the anthracite of Wales and the United States, are suitable, but generally they are mixed with coke. In Yorkshire, Durham, and Cumberland, coke is used. Charcoal, from its lower density and more ready combustibility, only requires a moderately heated blast of 100° to 200° C. On the other hand, with coal and coke, a blast 500° to 600° and even 700° is used.

By blowing in hot air the temperature is raised in the vicinity of the twyers. With cold blast a nose of chilled slag forms at the end of the twyer and gradually extends into the furnace, thus limiting its working capabilities. With hot blast it is necessary to cool the twyers, which are water-jacketed as a consequence of the high temperature to which they are subjected. Moreover, with hot blast the

conditions are more uniform and more under control; atmospheric conditions have less influence than with cold blast, and the zone of fusion is brought lower down in the furnace and concentrated within a smaller area. The economy in fuel and increased make per furnace when hot blast is used is due not only to the heat carried into the furnace by the blast, but also to the fact that furnaces of much greater capacity and larger hearths can be employed, larger burdens can be carried, and the heat more thoroughly distributed through the charge.

Twyers.—The twyers used for introducing the air into the blast furnace are subjected to intense heat, and require to be protected by a continuous circulation of water. They are therefore made with a double casing of wrought iron, cast iron, or bronze. Fig. 41 shows the arrangement of a

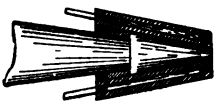


FIG. 41.

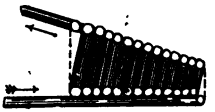


FIG. 42.

Staffordshire twyer. Another form, known as Lloyd's spray twyer, is open at the back, and the cooling water, in the form of spray, is driven from the end of a perforated pipe against the port of the twyer. Another form, termed the Scotch twyer (Fig. 42) consists of a spiral wrought iron tube enclosed in a cast-iron casing; a current of water circulates through the coil to keep it cool. Fig. 43 is a section of a water-cooled open twyer in use at the Hoerde Works. The number of twyers employed varies in different furnaces, according to the nature of the fuel and the character of the ore. An excess of blast causes the consumption of too much fuel, with the production of white iron; it also tends to cool the slag and impede the working by causing scaffolds. The cutting

action of the blast on the lining of the furnace is reduced by allowing the twyers to "overhang," that is, project for some distance into the furnace. But the more they overhang the less is the melting capacity of the hearth, as the melting space is limited by the distance between the opposite nozzles. With an insufficient blast the temperature of the furnace is lowered, and the production of iron lessened. With small charcoal furnaces two or three twyers are used. In large coke furnaces six or more are arranged symmetrically round the hearth, with their axes pointing a little away from the centre. When producing forge pig the twyers are arranged horizontally, or slightly inclined downwards, thus causing a partial decarburisation. For foundry pig the twyers are often slightly inclined upwards.

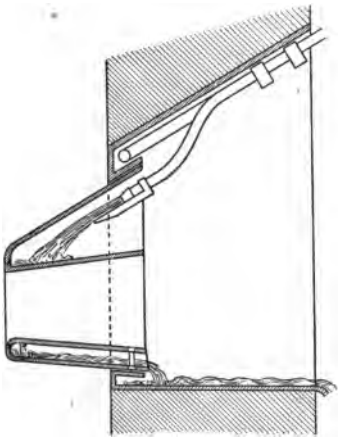


FIG. 43.

Collection of Waste Gases.—The waste gases of blast furnaces were formerly allowed to escape, the furnace tops being always left open; but this system has been almost universally abandoned, except in a few localities where fuel is cheap and cold blast is used. Various contrivances have, from time to time, been devised for closing the throat, so as to prevent the escape of the waste gases, which are conducted into suitable apparatus, where they are burnt to generate heat for heating the blast, etc., as before mentioned.

In the old charcoal furnaces of Sweden, and some old coke furnaces, a portion of the gases was collected without

closing the top, by introducing a number of iron pipes through the brickwork, at a depth of 10 or 12 feet below the top. In the Upper Hartz and other places, an annular space was formed in the upper part of the masonry of the furnace, communicating with the interior, beneath the surface of the charge, by a number of openings inclining upwards, in order to prevent the lodgment of the charge in them. A large pipe opened into the annular space and was connected with a high stack, so as to obtain the necessary draught for drawing off the gases. With some small straight furnaces a cast-iron cylinder is inserted in the throat, leaving an annular space which forms a collecting flue for the gases. The mode of charging by means of a central cylinder causes the more compact and finer particles to go to the centre and the larger pieces to the sides, which latter then become more permeable by the gases. In order to correct this defect a fixed cone (Fig. 44), supported by radial arms, is added, so as to distribute the charge more uniformly.

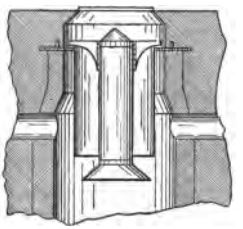


FIG. 44.

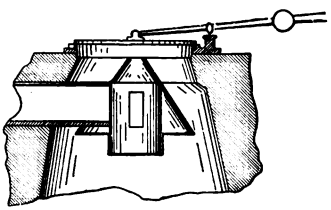


FIG. 45.

Escalle recommended a fixed cone without a cylinder (Fig. 45). The top being closed, the gas is collected by the cone, the radial arms which support it being hollow, so that the gases pass through them to the off-take. Movable cones are now more generally used, both for collecting the gases and distributing the charge. The most simple and general form consists of a fixed cup *a* (Fig. 46), and a

movable cone *b* suspended by a chain, so that it may be raised or lowered at will. Various contrivances are in use for controlling the movement of the cone, a frequent form being a

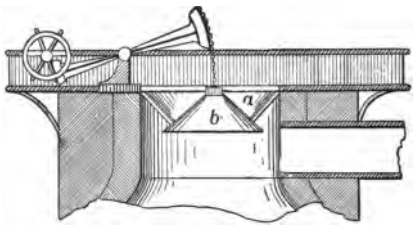


FIG 46.

pinion moved by a hand-wheel, and gearing into a rack attached to a counterpoise weight. The gases pass through a lateral flue into the main pipe, which conducts them to the heating stoves, boilers, etc At Ulverstone, in Cumberland, a central iron tube (Fig 47) lined with brick, has been adopted for collecting the gases. The tube is about 5 feet in diameter and extends about 5 feet into the throat of the furnace It rests on six ribs of brickwork. In Langen's apparatus the gas collecting tube is placed externally to the furnace, which may therefore be kept filled with the charge. It consists of a bell-shaped tube, which rests on an inverted conical charging ring. The bell is suspended from a lever, and the charge is placed in the conical ring, so that when the bell is raised the materials glide into the furnace

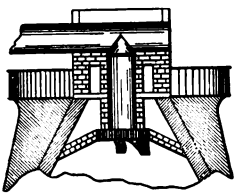


FIG. 47.

The Table on the following page shows the composition of the gases. No I. is from a small charcoal furnace. No. II. from hot blast modern Cleveland furnace, using coke. No. III. is from Scotch furnace burning splint coal.

The nitrogen passes through the furnace without taking any prominent part in the chemical changes, and forms more than half of the waste gases. The proportion of oxygen is much greater than that in the original blast, and this increase is obtained chiefly from the oxide of iron and the liberation of carbon dioxide from the limestone added as flux. When coal is used as fuel, vapours of tarry matter and ammonia are evolved in the gases, by distillation of the coal in the upper parts of the furnace. These compounds are recovered in some works, as at Gartsherrie, in the west of Scotland, where 40 gallons of crude tar, or 16 gallons of boiled tar and 22 lbs. of sulphate of ammonia, are obtained per ton of coal consumed.

COMPOSITION OF THE WASTE GASES BY VOLUME.

	I.	II.	III.
Nitrogen, - - -	62·34	54·91	57·50
Carbonic oxide, - -	24·20	26·66	27·50
Carbon dioxide, - -	8·77	18·36	5·25
Marsh gas (CH_4), -	3·36	—	—
Olefiant gas (C_2H_4), -	—	—	3·05
Hydrogen, - - -	1·33	0·07	6·70

The higher the ratio of carbon dioxide to carbonic oxide in the escaping gases the greater is the economy in the consumption of the fuel, and the lower the temperature at which they leave the furnace the less is the waste of fuel. The richer the gases are in carbonic oxide and hydrogen the greater their heat-producing power, so that when the furnace is working with the greatest economy the calorific value of the gases is lowest. Analyses of the gases taken at different depths below the throat show that the relative proportions of carbon dioxide to carbonic oxide vary in different zones. Thus while in the upper part of

the hearth the gases are chiefly nitrogen, carbonic oxide, and a little hydrogen; the amount of carbonic oxide diminishes and the carbon dioxide increases as the distance above the twyers is greater, up to a certain point, when the percentage of carbonic oxide again increases.

Cast-iron Stoves.—Fig. 48 represents an old form of stove, which consists of a series of arched pipes of cast iron, arranged in an oblong fire-brick chamber; along each of the long sides of this chamber is a tubular main, fitted with sockets, into which the legs of the vertical pipes are received, while between the mains, and running the full length of the stove, is a rectangular fire-place. The pipes are unequally expanded by the heat, and this, when the extremities are fixed to the mains, leads to frequent breakages. The defects of this arrangement have caused many modifications to be introduced. Thus the horse-shoe pipes have been replaced by an inverted **V** shape, which gives a smaller radius of curvature to the arch; and greater uniformity of heating the gas is obtained by introducing stops at intervals in the entry main, so that the air passes alternately backwards and forwards across the arch. In some works, the vertical pipes instead of being arched are united by short horizontal limbs at right angles, and are placed close together.

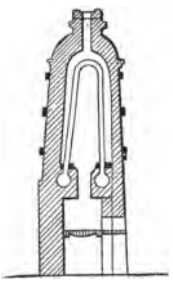


FIG. 48.

In many old German works a number of horizontal pipes of elliptical section were arranged in a fire chamber, in a similar manner to the tubes in a locomotive, and united in a continuous serpentine coil by arched bends, which were external to the fire, thus lessening the tendency of these bends to break by irregular expansion.

Of the regenerative type, two principal forms are employed, invented respectively by Cowper and Whitwell.

Cowper's Stove (Figs. 49, 50) is a circular wrought-iron tower, closed with a dome-shaped roof, and lined internally with fire-brick. It contains a fire-brick flame flue *A*, into which the waste gases from the blast furnace pass through the valve *B*. The body of the stove is occupied by checker-work of fire-brick for absorbing the heat. When the bricks are placed together they form upright hexagonal passages, the walls of which are 2 inches thick, and the longer diameter 7 inches wide. The gas entering the flue *A*, is there burnt, the air necessary for combustion entering through the valve *C*. The hot products passing down through the checker-work make it red-hot, and finally pass into the chimney flue *D*.

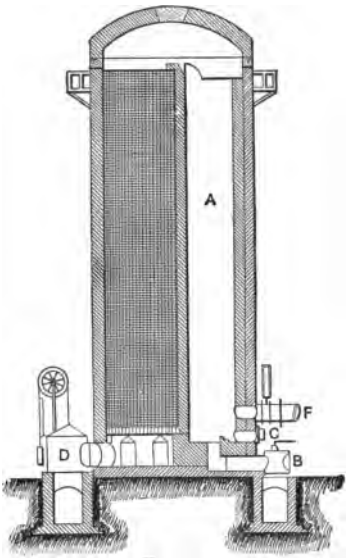


FIG. 49.

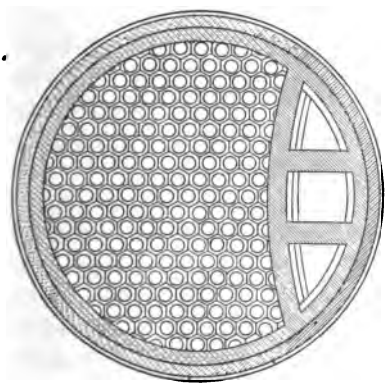


FIG. 50.

The stove having been thus heated, the valves *B*, *C*, and *D* are closed, and the cold-blast valve at the bottom of the stove opened, together with the hot-blast valve *F*. The cold air enters at the bottom or cooler end, and ascends through the brickwork, getting gradually hotter, and then escapes through the valve *F*, which communicates with the blast furnace, at a temperature of 800° C., which is the temperature of the stove. Two stoves are worked in conjunction, one being heated by the combustion of the waste gases, while the other is being utilised in heating the blast. These stoves are usually 60 to 70 feet high, and 25 to 28 feet in diameter. This stove is liable to be choked with dust, if a dust catcher is not used in the downtake pipe from the blast furnace. Dust is removed by firing a cannon in the stove, or by using special valves such as Lister's, which allow of the instantaneous release of the air.

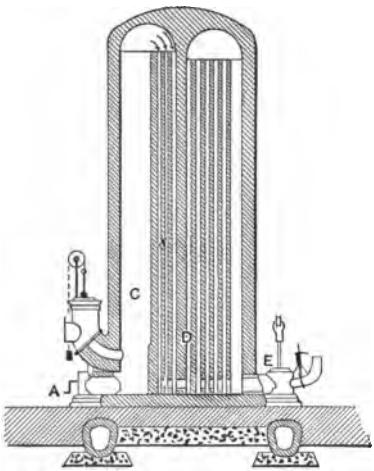


FIG. 51.

Whitwell's Stove (Fig. 51) differs from Cowper's chiefly in the arrangement of the absorbing brickwork. The air for the combustion of the waste gases is admitted at several points of the stove, so that the combustion is rendered more perfect. The regenerative brickwork is built so as to form a number of long, narrow vertical chambers, communicating with each other at the top and

bottom. The blast furnace gases enter through *A*, and meeting with warm air, introduced through suitable passages, combustion takes place, and the flame rising up *C*, passes down the narrow passages, etc., to the bottom. Here more air is admitted to burn completely the unconsumed gases, which rise up *D* and pass down through another series of narrow channels, finally leaving at the chimney valve *E*. In this respect it differs from Cowper's stove. When the stove is sufficiently heated, which takes about two hours, the gas and chimney valves are closed and the blast valve opened, the blast entering in reverse order to the gases, as in the Cowper stove. This stove offers less facilities for accumulation of dust, and affords greater facilities for cleaning. It is, therefore, used with furnaces smelting dusty ores.

It is advisable to place the stoves as near to the furnace as is consistent with the other arrangements of the works, in order that the blast may retain as much of its heat as possible. With some charcoal furnaces the stoves are placed on a level with the furnace top, and the hot-blast main carried down vertically to the twyers; but much greater regularity of draught, and freedom from dust is secured by bringing the waste gases to stoves on the ground level.

Ford and Moncur Stove[1] (Fig. 52).—This is a regenerative stove of brickwork enclosed in the usual air-tight cylindrical casing of iron or mild steel plates. The dome has a man-hole for access to the interior. A minimum space of ½ inch is allowed for expansion between the casing and brick lining. The combustion chamber is rectangular, and extends transversely the full width of the stove. In the upper part is an auxiliary regenerator, formed of 9 inch and 4½ inch walls, leaving parallel passages. The

[1] *Journal Iron and Steel Inst.*, No. 1, 1896.

segmental spaces on both sides of the combustion chamber are filled with regenerative brickwork, consisting of parallel walls, 2¼ inches thick. Each segmental space is divided into two equal portions by a cross wall 14 inches thick, extending from the base to the top of the stove, and uniting with the central division wall of the auxiliary regenerator. Below the grids carrying the division walls in each compartment is a vacant space, communicating with the central flue leading to the chimney valve, through an opening formed in the division wall, in which is fixed an internal valve, operated from the outside of the stove by a screw and a hand-wheel. These four valves constitute a feature in the arrangement. for by them the quantity of air passing through any of the compartments can be controlled, if at the commencement of blowing two or more compartments be shut off and held in reserve, to be gradually brought into action as the temperature begins to fall.

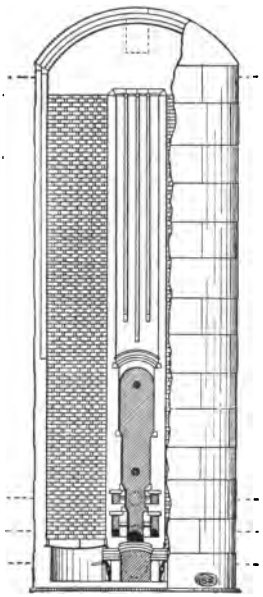


FIG. 52.

At the end of the central flue is a balanced mushroom valve, by which connection is made with the chimney flue. The instantaneous valve immediately in front has a butterfly flap, hung eccentrically, and so placed that when exposed to a pressure from the inside of the stove, it flies open automatically as soon as the catch holding it in position is disengaged.

The gas supply enters the combustion chamber through a series of graduated openings. The air supply is regulated with valves at opposite sides of the stove. After passing through the auxiliary regenerative chamber the heated gases are distributed and flow downwards through the main checker work. The form of the bricks in the checker work is dormer-shaped at the top, so as to prevent dust accumulating on them. The stove being divided into four separate parts by vertical walls, the blast of air may be turned on to each separately to remove the dust, Lister's instantaneous valves being used. Where the gases are very dusty, as with Staffordshire coal, the stoves are cleaned at every change from blast to gas. Hot-blast valves are very liable to have the seats burned, producing leakage, so that the valves are now made of cast-iron discs, with a hollow cast-iron seat, through which a current of air circulates from the cold-blast main.

The stove is 72 feet high and 26 feet in diameter. The heating surface of the combustion chamber and the auxiliary regenerator is 7320 square feet; the main regenerative chambers and passages, 58,680 square feet, making a total of 66,000 square feet. The cost of the stove, erected complete, exclusive of foundations and connections is £1600

Massick and Crookes' Stove.—The regenerative brickwork of this stove is on the Whitwell plan, but arranged on the "three-pass" system. The main combustion flue is in the centre of the stove, and the gases pass once down and once up through the regenerative brickwork. The object of this is to get a fuller duty out of the heat than in the ordinary "two-pass" system. The height varies from 57 to 70 feet, and the diameter from 17 to 21 feet. The products of combustion pass out at the top by a chimney, which is usual in American stoves.

The advantages of hot blast are: (1) Economy of fuel, since less fuel is required, also the heated oxygen has a greater affinity for the carbon and hydrogen of the fuel; (2) the blast penetrates the fuel more freely on account of its density being less; (3) under equal circumstances, less pressure is required for hot than for cold blast; (4) irregularities are better overcome with hot blast; (5) it facilitates and accelerates the blowing in of a furnace. The disadvantages are: (1) The pig iron is liable to be more impure, since silica, phosphoric acid, etc., are reduced to a greater extent, and (2) in consequence of the higher temperature, the furnace walls are more quickly destroyed.

Blowing Cylinder.—This is used for supplying compressed air to the blast furnace. It resembles a steam cylinder, but is of larger dimensions, and the lateral openings for admission of air are often omitted. The piston is made of plates of cast iron fixed on an iron or steel shaft. On the circumference are arranged two leather rings which press against the sides of the cylinder, one for the up and the other for the down stroke. To avoid friction, fine plumbago dust is projected against the interior of the cylinder from time to time. Two sets of valves are arranged on the cylinder cover at each end; the longer series open inwards for the admission of air as the piston recedes, and close at the return stroke; then the other series or discharge valves open and allow the compressed air to pass out.

Blowing cylinders do not furnish a regular supply of air, the air being compressed most at the middle of the stroke; hence a "regulator" is placed in the course of the main between the engine room and the furnaces. The regulator is a cast-iron cylinder, open at the top and closed with a weighted piston. When the supply of blast is greater than is required, the piston rises; but when the quantity diminishes the piston falls, and exerts a compressing force

until equilibrium is restored. If the blast main is of considerable length, or includes stoves, the regulator is unnecessary.

Lifts.—In hilly countries the blast furnace may be erected in a valley, the top being on a level with the ground. The charge is then tipped in without special apparatus. In most cases this is not possible, and lifts are required for raising the materials. These are of various kinds.

The inclined plane (Fig. 53) consists of a railway, between the ground and the top of the furnace, inclined at an angle of 30°. On this incline runs a platform carriage, triangular in vertical section, with two unequal pairs of wheels. The power is supplied from a steam engine working a winding drum, around which passes a wire rope or flat-linked chain.

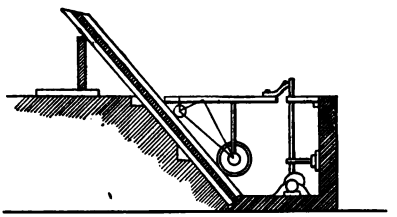


FIG. 53.

Colliery Lift.—This consists of a cage moving between vertical guides similar to those used in the shaft of a coal pit. It is worked by a direct-acting engine, fixed either on the ground or on the charging platform.

Water Balance.—This is a simple and effective lift still in use at several works, although more power is required for pumping water to the furnace top than for working a direct lift; it is also difficult to keep the water boxes tight. It consists of two cages moving vertically between guides, and connected by a chain passing over a pulley. Below the floor of each cage is fixed a water-tight box provided with a discharge valve. When one cage is at the top, having discharged its load, water is caused to flow into its box until

the weight is sufficient to pull up the other cage which is loaded.

Pneumatic Lift.—This form of lift is now frequently used, the areas of the cylinders being adjusted for a pressure of from 4 to 7 lbs, so that the force of the air in the blast-main is sufficient to raise the required load. Gjer's lift (Fig. 54) consists of a large cast-iron ram, which works in a 36-inch cylinder, rising the whole height of the furnace. From this piston pass wire ropes over four pulleys down to each corner of the lifting table, which is sufficiently large to hold four barrows. The weight of the ram is greater than that of the empty lift, and when the latter is at the top the ram will be at the bottom; so that by applying pressure beneath the ram it rises, and the table is lowered. The loaded table is heavier than the ram, but when air is removed from under the ram a partial vacuum is formed, and the atmospheric pressure brings it down, and consequently lifts the loaded table up to the furnace throat.

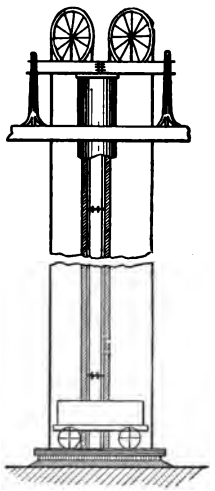


FIG. 54.

Recovery of Tar and Ammonia.—In the year 1884 experiments were conducted with a view to the recovery of tar and ammonia compounds from the waste gases of blast furnaces, and the results being encouraging, the plan was applied to several furnaces, especially in Scotland, where the coal is well adapted for such a process. At the present time the method is practically universal in Scotland. The size of the gas pipe has been enlarged, and all obstructions, such as sharp bends, have been avoided as much as possible.

Formerly, water coolers and high scrubber towers were the rule, but these have been replaced by the tar washer and horizontal liquor washer, which give an almost complete abstraction of ammonia and require little attention and repairs. They have the further advantage of holding only small quantities of gas in each compartment, thus avoiding the danger of a serious explosion. The most approved form is due to Mr. A. Gillespie of Glasgow. The following description of a plant of the Summerlee & Mossend Co. is given by Mr. H. Bumby:[1]

"The plant consists of seven furnaces. The gas is taken from the blast furnaces at a little over 300° F., in a tube of 9 feet diameter, to the tar washer, a horizontal vessel 64 feet long and 16 feet wide, in which the gas is split up and made to pass in thin streams under diaphragm plates sealed in tar. The hot gases are then brought into intimate contact with the tar; the operation is twice repeated in a vessel to ensure complete contact, with the result that the temperature is reduced by 130° F., and the heavier tars contained in the gas are entangled and deposited, flowing slowly along the bottom of the washer to the regulating valve, where they are automatically run off to the stock tank."

"The tar fed into the tar washers is the lighter tar from the liquor washer and condensers, containing a large excess of water and gas: by the same operation these are expelled and the tar heated and prepared for distillation in the tar stills."

"The partially cooled gases pass from the tar washer to the air condensers, where they are again split up and pass into twelve boxes leading into a series of twenty-inch vertical tubes, having a total length of about 4½ miles. In passing through these the temperature of the gases is

[1] *Journal Iron and Steel Inst.*, No. 2, 1901.

brought down to that of the atmosphere, and they are in a fit state for the complete recovery of the ammonia in the form of liquor. From the condensers the gas passes into the exhausters, of which there are three sets of the horizontal cylinder type, each actuated by a pair of steam cylinders, 18 inches diameter with a 4 feet 6 inches stroke. The two gas cylinders are 6 feet in diameter, by the same stroke, each pair of exhausters being capable of passing 915,000 cubic feet of gas per hour of 30 strokes per minute, or in all about 2,750,000 cubic feet per hour. The two liquor washers are horizontal, 60 feet long by 12 feet 6 inches wide, in each of which the gas is repeatedly split up and impelled under diaphragms sealed in liquor, the first washer being fed with weak ammonia liquor, and the second with a small quantity of pure water. The products recovered in the condensers and liquor washers pass into specially constructed separators, where, by the difference in specific gravity the heavy and light frothy tars are each separated from the ammonia liquor. The washed gas is then used for heating the stoves, boilers, etc. The tar is dealt with in separate tar stills, distilled and graded, and the pitch run into blocks, etc. The sulphate of ammonia recovered in various works varies from 20 to 25 lbs. per ton of coal used, and the pitch and oil from 150 to 200 lbs."

The washed gas is found to be suitable for gas engines.

CHAPTER XII.

REFINING PIG-IRON.

Two distinct methods have been adopted for the conversion of pig iron into wrought iron, depending on the kind of furnace employed, viz., *the open-fire or hearth-finery*, and the *puddling-furnace*, which is of the reverberatory type. The chemical reactions are similar in both cases, being based on the oxidation of the impurities by oxygen, both in the gaseous and in the combined form.

Open-fire or Finery.—In former times this hearth was termed a "bloomery" from the nature of the product, which was called a bloom. The hearth is rectangular, and formed of cast-iron plates lined with charcoal, the bottom being exposed to a current of air in order to keep it cool. Three sides are vertical, while the remaining side slopes a little outwards In the simplest or German forge the flames escape into an open hood, but in the Swedish forge the hearth is covered with a cylindrical roof, and communicates with the chimney by a lateral flue. The fuel employed is charcoal, the fire being blown by a blast of air issuing from a single twyer. A view of the finery in vertical section is given in Fig. 55.

In the open-fire the iron is placed in contact with the fuel. Now this intermixture is objectionable, because the

refining is based on oxidation, and the fuel acts as a reducer, so that that which the air oxidises, the fuel tends to deoxidise, the purification being retarded thereby. The consumption of fuel is also very great. If the iron is designed to retain some carbon, so as to produce a steely product, then the open-fire is admissible.

The charge of pig iron, usually in broad thin plates, is placed on a bed of glowing charcoal, which reaches to the level of the twyers. The operation of refining is hastened by the addition of hammer scale and rich slags, which assist in oxidising the impurities. The fusion of the iron is allowed to take place gradually, so as to expose it for a lengthened period to the oxygen of the blast. At the moment of fusion the foreign elements begin to be rapidly oxidised. The silica unites with the oxide of manganese and oxide of iron to form a fusible slag, which, in consequence of the excess of metallic oxides, is a basic silicate.

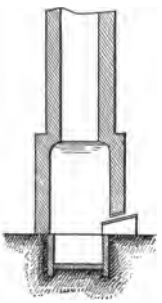


FIG. 55.

The ferrous oxide, FeO, acts as a vehicle for oxygen, uniting with the gas, and being converted into the black oxide, Fe_3O_4. The latter coming in contact with the impure iron, oxidises the impurities, itself being reduced to FeO. After a time the slag becomes neutral, and is in part removed; then fresh basic slag and hammer scale are added. To complete the operation, the masses of iron are lifted up to the twyer level in order to completely oxidise the combined carbon. The white-hot mass of iron, which is now of a spongy texture, is then taken to a heavy hammer and compressed to a slab, termed a "bloom." The subsequent treatment of the bloom varies in different districts. In Italy the partially refined mass is removed from the hearth and cooled with water; then

broken up, and reheated sufficiently to cause the iron and slag to cake together, when it is again removed. In the third stage the iron is reheated with rich slags until it is sufficiently refined.

In South Wales a superior quality of iron sheets for tin-plate was made from the best pig-iron in a charcoal finery. The pig iron was first partially refined in a hearth termed a "refinery," which will be subsequently described. The charge of 2½ to 3 cwts. of refined iron from a coke "refinery" produced a finery ball, weighing about 2 cwts., which was shingled and drawn out to a long bar, 2 inches thick, under a lever-hammer. The bar was then nicked and broken into pieces, the best pieces being selected, and made into small bundles or piles. These bundles were reheated in the flame of a coke-fire, in a special furnace known as the "hollow-fire," the upper part of which formed a chamber in which the piles were reheated. The piles were then welded under a hammer and rolled into sheets. Before finishing, the sheets were annealed, pickled in sulphuric acid, and then rolled cold. Finery slag is highly basic, containing upwards of 75 per cent. of ferrous oxide, FeO.

The Swedish-Lancashire finery is arched over at the top, and communicates with the chimney by a horizontal flue in which the pig iron undergoes a preliminary heating before being drawn into the hearth itself. The fuel used is charcoal, and the blast is heated to 100° C. by passing through a series of iron tubes, heated by the waste gases of the finery. The hearth is first covered with charcoal, and on this is placed, from the flue, about 2 cwts. of the pre-heated pig iron. The blast is then turned on and more charcoal added as required. The metal during the melting is oxidised, and when it begins to liquefy it is partially refined and decarburised before it reaches the bottom, when it is again partially solidified. The workman breaks this up with iron

bars and lifts it up to the front of the twyer for further oxidation of the carbon and other elements As the decarburisation proceeds, the metal becomes less fusible, the workman raises it to the top of the fire and adds fresh charcoal. The temperature is now raised by increasing the blast so as to again melt the iron and separate the slag with which it is mixed. The purified metal is then collected into a ball, which is taken to the hammer and shingled into a bar. The bars are cut up into suitable lengths, piled, reheated in a separate fire and welded under the hammer and rolled into bars. About 150 lbs. of charcoal are required for 100 lbs. of bars produced, and the loss of weight of the pig iron charged in is about 15 lbs. In Sweden this hearth is worked with three twyers.

Styrian Open Hearth.—The metal produced in this hearth is termed "raw steel," which is somewhat analogous to blister steel. The works are supplied with power from the rivers of the Styrian Alps by means of breast water-wheels and turbines. The hearth is rectangular in plan, being about 30 inches long by 20 broad. The bed of the furnace is formed of four inclined iron plates, three of which incline outwards and the fourth inwards. The twyer is fixed in one of the end plates, inclined downwards at an angle of 20 degrees, the eye being about $1\frac{1}{2}$ inches in diameter. The blast is heated to about 160° C., and worked at a pressure of about half a pound to the square inch. The fuel used is charcoal, which is charged into the hot hearth, and a shovelful of slag introduced. Then the white pig iron, obtained from manganiferous spathic iron ores, and previously cast in thin slabs or plates, is added. It is held in tongs over the blast until it melts and falls down into the hearth. The metal is at first quite fluid but afterwards becomes pasty, in consequence of the removal of the carbon by the oxidising

influence of the blast and the basic slag previously added. Another slab of cast iron is then melted as before, and so on with other slabs. After this it is essential that the temperature should be lowered as soon as possible, and to do this the slag is tapped off, cooled in water, and a shovelful of the wet slag added. The raw steel is now in the form of a lump, the top of which is some two inches below the twyer. The lump is lifted out, allowed somewhat to cool, and taken to the hammer. Such a lump weighs about 200 lbs. It is divided into wedge-shaped masses, each of which is hammered then reheated and hammered into bars. The charge of pig iron is about 2 cwts. The loss of metal is about 22 lbs. It is claimed that any kind of metal can be produced in this furnace, from the softest wrought iron to the hardest tool steel.

Refining in the Refinery.—For the better qualities of wrought iron, crude pig iron was formerly submitted to a preliminary operation in a rectangular hearth, termed a refinery (Fig 56), with a number of twyers so arranged on two of its sides as to project a stream of air on to the molten iron, in order to oxidise its impurities. The iron was finally quenched, by running it into an iron trough, thus causing the carbon to remain in the combined form, which condition greatly facilitates puddling by the original "dry" method, as white iron assumes a pasty state before melting.

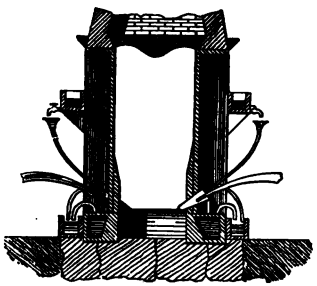


FIG. 56.

The hearth consists of a cast-iron framework with a sandstone or firebrick bottom, and is surmounted by a low brick chimney, bounded on its sides and back by hollow iron

castings, through which a current of water is made constantly to circulate. The front of the hearth is closed by a cast-iron plate, having a tap hole for the metal and slag. The casting mould, placed in front of the hearth, is also made of thick cast-iron plates, and is about 3½ feet wide by 10 feet long by 8 inches deep. It is placed upon the edges of two long cisterns, through which water circulates for the purpose of cooling the mould, which quickly cools the refined iron when it is cast.

The iron, in the form of pigs and scrap, is placed in alternate layers with coke upon a bed of ignited fuel at the bottom of the hearth, and the blast supplied at a pressure of 1½ to 2½ lbs., according to the combustibility of the coke. In about 2 to 2½ hours the charge is melted, and in another hour the blast has sufficiently oxidised the impurities in the iron. The refining is hastened when basic iron-slags and hammer-scale are added to the charge.

The element whose chemical affinity for oxygen is greatest will unite with this gas first, and others will be oxidised in turn in proportion to their chemical energy. The order of oxidation will be as follows :—Silicon, manganese, phosphorus, sulphur, carbon, and iron. But this order will be modified according to the temperature employed and the kind of slag present. Also oxygen will combine with the dominant metal by the influence of mass, so that refining slags always contain a large amount of oxide of iron, and may be represented by the formula, $2FeO . SiO_2$.

The refined metal, forming a plate 3 inches thick, shows a silvery-white fracture, the lower part being compact, and the top part dull and cellular. The metal is very brittle, and is readily broken into pieces suitable for the puddling process.

Puddling—Dry Way.—The method of dry puddling in a reverberatory furnace was developed by Cort, and patented by him in 1784. The furnace-bottom was dished out and

lined with sand, which became thinly glazed over with slag during the working. In later years the bottom was covered with a lining of oxide of iron, formed by oxidising scrap iron in the strongly oxidising atmosphere of the furnace. Each operation was composed of three periods—fusion, rabbling, and forming the blooms. White or refined iron was chiefly used. About 4 cwts. of refined metal were charged into the furnace, and partially melted in about half an hour, forming a pasty mass, which did not become liquid as is the case in wet puddling. It was then stirred with iron tools so as to bring all parts under the oxidising influence of the air. As the impurities were removed the iron became less fusible, requiring the temperature to be gradually raised The particles of iron were then collected into balls by the puddler, each ball weighing about 80 lbs.

The original furnace was of the ordinary solid type, and although the use of scrap iron was recognised, it had to be oxidised by the air before it could be of use in purifying the pig iron. In fact, the purification was either directly or indirectly caused by the oxygen of the air, and only white iron was admissible. The readiness with which silica unites with oxide of iron caused great waste of iron, and it was usual to produce only one ton of puddled bars from two tons of pig iron charged in. The operation was very slow, and the siliceous lining wore away so rapidly that the re-lining of the bottom was necessary after each charge. The old refinery was then brought into requisition to partially purify the pig iron before its introduction into the puddling furnace. As the product of the refinery was white cast iron, it was adapted to the dry method of puddling, in which the iron never gets very fluid, but is in a more or less pasty condition, and was rabbled in that state until sufficiently purified. In fact, the term "puddling" was originally confined to the working of refined iron.

The reactions in the puddling process are similar to those in the old finery. The first effect is to cause the graphite to pass into combined carbon, as only the combined carbon is oxidised to any extent. The carbon is then oxidised to carbonic oxide, which burns with its characteristic blue flame on the surface of the metal.

Wet-puddling or Pig-boiling.—This method of puddling was introduced about 1830, by Joseph Hall of Tipton, who used old furnace bottoms as a material for lining his furnace. This material, containing much oxide of iron, greatly shortened the process and enabled him to dispense with the refinery. The old brick furnace was discarded and replaced by a frame of air-cooled iron plates as in the present form. This frame furnace was lined with calcined tap cinder (bull-dog), which is still partially used. This method is characterised by the complete fluidity of the pig iron and the length of the puddling, which often lasts over an hour, so that the whole process requires about two hours. The preliminary refining being dispensed with, the pigs submitted to this process may be siliceous and strongly carburetted, and should be manganiferous if steel is desired. Now manganese retards the decarburisation of the iron, by constantly reducing magnetic oxide Fe_3O_4 to ferrous oxide FeO, and ferrous oxide to metallic iron, which reduction would otherwise be effected by carbon; in fact as long as the iron contains manganese its superior affinity for oxygen practically prevents Fe_3O_4 being formed. Moreover, slags containing oxide of manganese are more fluid and more easily expelled by shingling and reheating. A little manganese in steel also improves its quality.

The bed and sides of a modern puddling-furnace are lined with refractory materials rich in oxide of iron. The furnace is first charged with fluxing cinder or "hammer slag," and then $4\frac{1}{2}$ cwts. of grey forge pig iron are added. The iron

and cinder should become pasty and melt down together. The iron becomes thinly liquid when melted and thus differs from white pig iron as in the dry process previously described. When the iron is melted, it is between two oxidising influences—the air and oxide of iron—and the operation will be shorter and the product more uniform in proportion as the rabbling (or moving of the mass by the tools of the puddler) is more vigorous, because by that means a more thorough mixture of the iron and oxidising substances is effected. The ferruginous slag formed takes up oxygen from the air, causing FeO to pass into Fe_3O_4, which then helps to oxidise the impurities, chiefly in the order of their oxidisability, viz, silicon, manganese, phosphorus, possibly sulphur, and carbon.

The period of rabbling has two distinct phases—1°, the scorification of silica and oxide of manganese; 2°, the very agitated period, termed the "boil," when decarburisation occurs, the bath of metal being covered with jets of burning carbonic oxide. The forcible ejection of this gas causes the slag and globules of iron to be lifted up, giving the appearance of a liquid when boiling. As the carbon is removed the iron requires a higher temperature to keep it liquid, and particles of iron begin to solidify and join together, or, as it is technically termed, "come to nature," and form a spongy, sparkling mass of iron grains. The temperature is now raised to the highest point, so as to bring the iron to a welding heat. The metal is then collected into balls by the workman.

The excellence of the iron produced will mainly depend on the prevalence of a high temperature during the boil, so as to maintain a highly oxidising atmosphere; for if the temperature be too low, the reducing flame of carbonic oxide prevents the complete liberation of carbon, and hard iron or steel results. The quality of the iron will also

depend on the kind of pig iron operated upon, for the greater the quantity of impurities, especially phosphorus and sulphur, the more prolonged must be the puddling, and the greater will be the waste of iron. The slag from a puddling-furnace is essentially a silicate of iron, containing many of the impurities originally present in the iron, and is termed "tap-cinder."

Yorkshire Method.—The celebrated brands of iron, known as Bowling and Lowmoor, are made by a process intermediate between that of the dry method and the wet method. Cold blast pig iron is used. This iron is first treated in refineries, the plate metal thus obtained being reheated and charged hot into the puddling-furnace, where a high temperature is used. The metal being free from silicon and of high quality is soon refined, and the slag being basic, takes up the phosphorus. The balls of iron produced are shingled into blooms or "noblins" about 12 inches square and 2 inches thick. They are then broken, the most fibrous and least crystalline ones being selected for the best iron. These are piled, reheated, and welded into billets, and after again being reheated are rolled into bars. The success of the process lies in using good pig iron and selecting only the best portions of the puddled blooms. It is uniform in quality and stands several times reheating and welding without deterioration. Best Yorkshire plates have a tensile strength of 22 tons per square inch with the grain, and 20 tons across the grain, with an elongation of 16 per cent. in the former and 10 per cent. in the latter. Bars have a tensile strength of 24 tons per square inch and 25 per cent. elongation.

Russian Sheet Iron.—These sheets are prepared with a dark-grey glossy surface, which does not crack like ordinary scale on bending the sheets. The iron is obtained from

ores in the Ural Mountains, and smelted with charcoal and cold blast. The pig iron is refined in puddling-furnaces. The puddled iron is crystalline and steely in character, it is rolled into bars, then cut up, piled, and reheated in muffles using wood as fuel. It is then welded and cross rolled into sheets, in packets of three, with charcoal powder between to prevent them sticking. The sheets are then cut to size, the defective ones rejected and the good ones again annealed in packets with a wood fire. The sheets are then made into packets of 60 to 100, and hammered with a smooth-faced hammer to improve the surface. For finishing, each sheet is placed between two finished sheets and again hammered in packets of 140 to 200 sheets. A first-class sheet must not have the slightest flaw.

Chemical Changes.—The question as to whether the oxygen in puddling comes from the fettling or from the air has been investigated by Lieut.-Colonel Cubillo.[1] He experimented with a charge of 484 lbs. of cold pig iron, and the furnace was coated with 398 lbs. of ore. 407 lbs. of balls were obtained, and 398 lbs. of slag, consisting of 363 lbs. of tap-cinder, 50 lbs. of hammer slag, and 3·3 lbs. of slag from the rolls. After charging, the iron was melted in 25 minutes; 14 minutes later the puddler commenced work, and the balls commenced to form after another 28 minutes, the first ball being drawn 8 minutes later, or 75 minutes after charging. Analysis of the pig iron and the balls showed:

	C.	Mn.	Si.	P.	S.
Pig iron, - -	2·85	0·540	2·720	0·440	0·160
Balls, - - -	0·24	0·005	0·015	0·015	0·008

[1] South Staff. Iron and Steel Institute, 1901.

Analyses of the ore used and of the slags were as follows:

	Tap-Cinder.	Hammer Slag	Rolls Slag.	Ore.
Silica,	13·750	16·980	8·130	11·450
Ferrous oxide,	59·540	56·570	62·360	—
Ferric oxide,	16·920	15·000	23·140	75 980
Alumina,	—	1·740	0·890	2·890
Lime,	4·100	4·650	2·180	1·850
Magnesia,	1·830	1·910	1·250	0·560
Sulphur,	0·090	0·148	0·097	0·027
Phosphoric oxide,	0·680	0·904	0·352	0·022
Manganese oxide,	1·160	2·040	1·260	1·030
Iron,	58·160	54·500	64·700	—
Phosphorus,	0·297	0·375	0·153	—

The loss is as follows:

	Percentage of Impurities.		Total Weight in Kilograms.		
	In Pig Iron.	In Balls.	In Pig Iron.	In Balls.	Oxidised.
Carbon,	2·85	0·240	6·270	0·444	5·86
Manganese,	0·54	0·005	1·190	0·009	1·18
Silicon,	2·72	0·015	5·984	0·028	5·96
Phosphorus,	0·44	0·015	0·968	0·028	0·94
Sulphur,	0·16	0·008	0·352	0·015	0·34

The author calculates from the weights of oxygen consumed by the iron and impurities that, out of a total of 61·73 kilograms, no less than 57·94 are derived from the coating of the furnace and only 3·79 supplied by the air. It is therefore considered that the oxidation of extraneous matters is effected by the change of ferric to magnetic oxide.

Plant.—A plant for producing wrought iron from pig iron usually consists of two separate parts, one termed the forge, in which are arranged the puddling furnaces, hammer, rolls, squeezers, etc., for dealing with the crude iron; the other,

termed the mill, which contains the reheating furnaces, with rolls for finishing and producing the desired sections. The floor is generally covered with iron plates for convenience of conveying the iron from the furnaces.

Puddling-Furnace.—The modern puddling-furnace (Figs. 57 and 58) is a single-bedded reverberatory, with a low flat

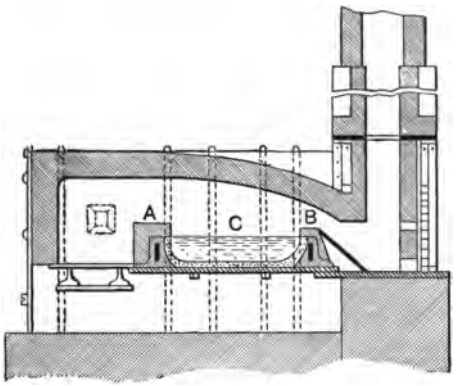


FIG. 57.

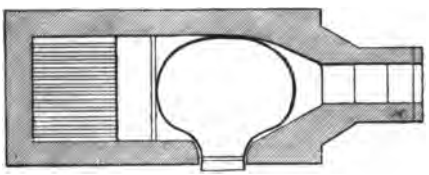


FIG. 58.

roof, generally slanting from fireplace to flue. The fire-bridge *A* and flue-bridge *B* are formed of hollow iron castings encased in fire-brick; the bed is likewise formed of iron plates rebatted together; and the sides sometimes consist of hollow iron castings. These hollow castings are kept cool by the circulation of air or water through them. The

laboratory or working part *C* is about 6 feet long and 4 feet wide, tapering towards the flue-bridge. The grate area varies from one-third to one-half that of the laboratory. The bed is lined with broken slags, hammer scale, and red oxide of iron, or puddler's mine, and the sides with bull-dog, all being well rammed down; this is termed "fettling." In Cleveland, burnt pyrites (blue billy) is used as a fettling. The working door is on the same side as the fire hole, and is made of fire-brick, set in an iron frame; it is suspended by a chain attached to a counterpoised lever. A flue is generally provided for each furnace and communicates with its own chimney, or passes into a boiler flue for utilising the waste heat. The flue slopes down towards the stack,

ANALYSES OF MATERIALS USED FOR FETTLING.

	Bull-dog.	Purple Ore.	Pottery Mine.
Ferrous oxide, - -	3·5	—	47·0
Ferric oxide, - -	64·0	95·0	—
Manganese oxide, -	—	—	2·6
Silica, - - - -	31·5	1·3	—
Lime, - - - -	—	0·5	3·4
Water and organic matter, - - -	—	—	12·0
Phosphoric oxide, -	1·0	—	—
Insoluble residue, -	—	3·2	2·3
Alumina, - - -	—	—	1·0
Carbon dioxide, - -	—	—	31·7

its sectional area being about one-fifth to one-seventh that of the fire-place. The draught is usually regulated at the top of the chimney by a damper, which is moved by a hanging chain. Two men are required for each furnace; the puddler and the underhand. About six heats are worked off in twelve hours, the charge being 4 to 4½ cwts. The smaller amount refers to grey iron, and the larger amount to mixtures of grey and white iron. The loss of weight

between the pig iron charged into the furnace and the puddled bars is 1½ to 2 cwts. per 22 cwts. of pig metal, or from 7 to 10 per cent. The coal required is about 20 to 22 cwts. per ton of puddled bars. The fettling materials required in a turn of 12 hours are from 6 to 7 cwts. of bull-dog and 2 to 3 cwts. of puddler's mine, in addition to the mill scale added to the charge.

Mechanical Puddling.—Many attempts have been made to lessen the enormous amount of labour which has to be expended in hand puddling, by substituting mechanical appliances. The methods proposed are—tools imitating manual rabbling, and rotating or oscillating hearths.

Mechanical tools are so arranged as to be capable of a compound motion over the bed of the furnace, one of the simplest being that of Eastwood, Fig. 59. The rabble is supported in a stirrup connected with one end of a bent lever, placed overhead, which receives a to and fro motion through a crank, and a lateral motion through a screw and wormwheel gearing; this double motion enables it to be worked over the whole bed. The machine is bolted to the back of the casing, on the working side of the furnace, and by means of a fast and loose pulley may be put in and out of gear at will.

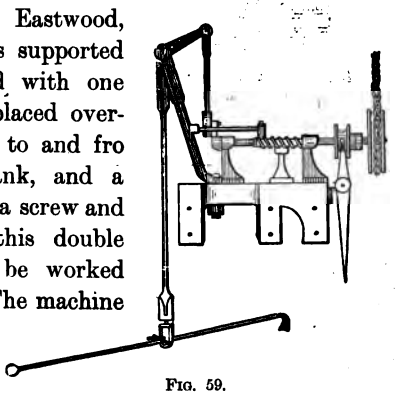


FIG. 59.

Danks' Furnace.—This furnace (Fig. 60) consists of a cast-iron cylinder with conical ends, 4 feet long and 5 feet 3 inches in greatest diameter, bound with iron hoops. The shell is formed of segments bolted together, and on the inside are twelve ribs which keep the fettling in position.

The cylinder is encircled at either end with a roller way, which rests on anti-friction rollers. One end of the chamber is open to the fire-place and the other end opens into an elbow-shaped moveable flue *B* leading to the chimney. The front conical cover has a tap-hole for the slag, and the charge is withdrawn at the chimney-end by removing the moveable flue. The fire-place has an air-blast *C* placed below the grate for increasing the combustion, and

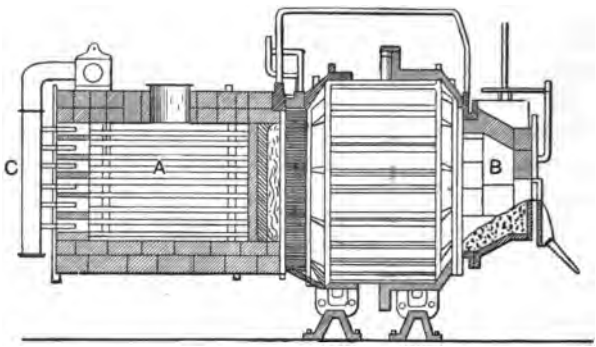


FIG. 60.

also small twyers in the back wall, through which air is blown at the level of the fire-bridge. The fire-bridge is hollow, being kept cool by a current of water, and fettled on the inside. The chamber is first lined with a mixture of crushed iron-ore and lime, made into a mortar, which is then dried by a wood fire made inside. Then on this initial lining is melted some iron-ore and hammer-slag, and into this, when liquid, are thrown pieces of "ilmenite" or harder ore, until the lining is studded with such pieces projecting from two to six inches. About 2½ tons of ore are required for fettling a 700 lbs. furnace.

The charge of pig iron is introduced at the chimney-end with 20 per cent. of cinder, and as it melts the furnace is

made to slowly revolve, so that the iron is continually exposed to the action of the air in all parts. The action is the same as in ordinary puddling. The speed is gradually increased as the operation proceeds, and when the particles of iron begin to adhere the speed is again reduced to two revolutions per minute. The iron is collected into one large ball, and removed at the flue end by a forked lever carried by a crane. The time required for working a charge varies from 1 hour to 1½ hours, according as white or grey iron is used Eight to ten charges may be worked with once fettling, and the consumption of 22 cwts. of coal per ton of iron. The oxidation of the impurities is chiefly effected by the oxides of iron in the fettling, and their removal is more perfect than by hand-puddling. A certain portion of the oxide of iron in the fettling is also reduced, so that one ton of puddled iron is obtained from 18½ cwts. of pig iron employed.

The disadvantages of the process are, that a large mass of 700 lbs weight has to be hammered or squeezed, requiring special appliances; the slag is difficult to remove completely from the interior of the mass; the wear and tear is very great, requiring frequent repairs; and the lining very soon wears away. Mr. J. Williams described the furnace thus: "As a worker of metals it is without an equal; as a melter it is inferior to many; as to endurance it is the shortest lived of any; and as to convenience of repairs it is one of the most difficult."

Gas Furnaces for Puddling.—By the use of gas producers, fuel may be used which is much too inferior for ordinary furnaces, and a higher temperature obtained by the combustion of the gas formed than by using solid fuel directly. The puddling operation is the same as usual, except in such arrangements as Pernot's, where gas may be used in combination with mechanical puddling. In the case of

Siemens' furnace the regenerators are liable to be choked with dust, slag, and iron, carried over during the boiling stage. This may be largely remedied by passing the waste gases through an intermediate chamber, so as to deposit the solid matter before entering the regenerators. In some cases certain ferruginous substances have been placed at the entrance of the regenerators to act as a kind of filter The difficulties arising from the deposition of dust, etc., have prevented the use of gas in many forges. The extreme heat produced in Siemens' furnace probably increases the affinity of iron for carbon, which renders the fining more difficult, and tends to produce an imperfect steely iron.

Gas furnaces for puddling were used so far back as 1840 in Carinthia, and later in Styria. Sir William Siemens introduced gas furnaces into this country in 1860. The Boetius system was used in 1870. Mr Price of Woolwich introduced a kind of gas furnace, in 1873, and the Casson-Bicheroux was introduced about 1880. The Pernot furnace was used in France in 1874.

The Casson-Bicheroux furnace is not a regenerative furnace, but simply a gas furnace, heated by gas from a producer. The air is heated by passing it under the neck and bottom of the furnace; and by thus equalising the temperature between the two currents better combustion is obtained in the furnace. In Staffordshire and Yorkshire it was found necessary to use blast, both for gas and air, owing to the nature of the coal. The advantage of this system is, that existing furnaces need not be interfered with, except to make the gas connections in lieu of the fire-place.

Siemens' Furnace.—Siemens enunciated the principle that pig iron can be refined by the action of a ferruginous lining, or by hammer scale or other forms of oxide of iron added to the charge. This was proved by using a regenerative gas furnace, which was lined and fed with oxide of iron.

The silicon and carbon are oxidised by the fluid oxide present, and the iron thus reduced is added to the charge, although this may be lost again in the subsequent stages. Fig. 61 shows the furnace in vertical section. The regenerators, although close to the furnace, are so placed that the bottom

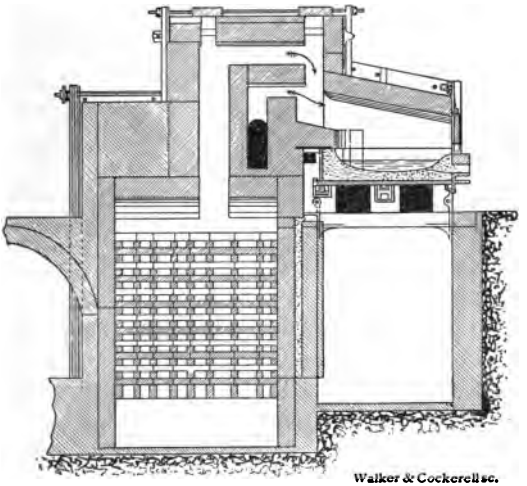


FIG. 61.

of the furnace is readily accessible for repairs. The gas furnace has the advantage of having the temperature more under control and an oxidising, reducing, or neutral atmosphere can be obtained at will.

Crampton's Furnace.—Mr. Crampton has introduced a revolving furnace, Fig. 62, similar to that of Danks, with a double casing, through which water circulates so as to preserve the lining. The essential feature of this furnace is the use of finely divided fuel as the source of heat. The ordinary fire grate is replaced by a tube-piece *t*, fitted into the end plate of the moveable flue-piece; it is bell-mouthed towards the flue, and through this tube a stream of fine

coal, mixed with the necessary amount of air, is injected automatically. Fig. 63 shows the feeding arrangement. The fuel is perfectly consumed, owing to its intimate

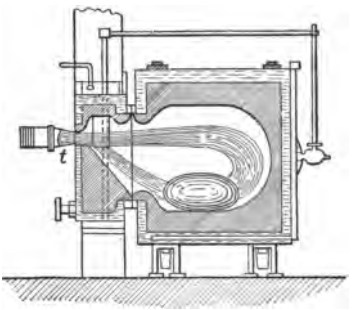


FIG. 62.

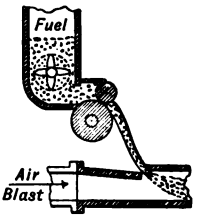


FIG. 63.

admixture with air, producing a high and regular temperature.

Pernot's Furnace.—M. Pernot at St. Chamond used a furnace with a fixed roof and circular revolving bed, inclined at an angle of 5° or 6°. It consists of three parts;—the fire-place burning ordinary fuel, or a gas producer for generating gaseous fuel; the puddling-chamber with moveable bed; and the flue leading to the chimney. Fig. 64 represents a Pernot furnace heated with gaseous fuel. The bed is made of hollow wrought iron segments, and fettled in the usual way with oxide of iron and cinder. Below the bed is a strong iron carriage moving on rails. This carriage has two pairs of wheels, and upon the framework is mounted the socket of the revolving axis of the bed. Rotation is imparted by

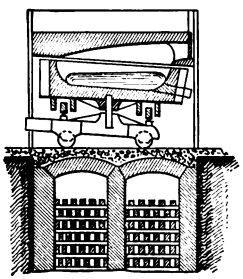


FIG. 64.

means of an endless screw and worm wheel, which is fixed to the circumference of the ring at the bottom of the bed. Conical friction-rollers are also provided to assist the central pivot in keeping the hearth in position as it rotates.

From 15 to 20 cwts. of pig-iron with some scrap iron are introduced, after having been previously heated to redness. The charge is rapidly melted, and when the refining is completed, the iron is balled up by workmen. From 9 to 10 charges are worked off every 24 hours. The inclination of the bed causes the lining to be alternately under the molten iron and exposed to the flame, so that the bottom heat is constantly renewed and sticking of the charge prevented. Moreover, the exposure of the lining at each revolution favours oxidation, so that any FeO which has been reduced by the carbon of the pig-iron, is again converted into Fe_3O_4. The rotation not only rabbles, but promotes the reaction of the lining on the pig-iron. The disadvantages of this method are:—the great initial cost, the large quantity of fettling used, and the rapid wear of the bed, while the manual labour required is the same as in an ordinary furnace, although the work is much less fatiguing The advantages are:—the large increase of metal refined in a given time, with a great economy of fuel, which is its principal advantage. The bed being removeable, the roof is readily accessible for repairs, and a new bed can be run under and worked while the old one is being mended.

Waste Heat.—The waste heat of furnaces used for refining iron has been utilised in a variety of ways, but chiefly for heating steam-boilers. The commonest form of boiler is a vertical cylinder with hemispherical dome, placed in the chimney. The flame passes round it, or through a central flue connected with the outer shell by horizontal tubes. Two furnaces are generally connected with one boiler.

At Rhonitz a combination of puddling and reheating furnaces was adopted. An ordinary gas-producer using wood fuel was combined with three hearths in one straight series. The first was used for reheating, and received the hot gases without air. The second was the puddling-furnace where the gases were burnt by admitting air at the fire-bridge. The third was heated by the waste heat from the puddling-furnace, and used for heating the pigs previous to puddling. Lastly, a hot-blast stove was placed in the base of the chimney, by which means the air employed in the puddling-furnace for burning the gases was raised to 200° C.

The method of using the waste heat in Siemens' furnace is described with Fig. 61. A somewhat analogous plan is employed by Ponsard (see Fig. 80).

The loss in puddling varies, according to the impurities in the pig-iron employed, from 5 to 10 per cent.; and the fuel consumed is from 20 to 25 cwts. per ton of puddled bars produced. The charge of pig-iron for an ordinary puddling-furnace is 4 to 4½ cwts., and in Staffordshire 5 to 7 heats are worked off in 12 hours.

CHAPTER XIII.

TREATMENT OF PUDDLED-IRON.

THE operations which are conducted in that part of an iron-works known as the "forge," include puddling, shingling or hammering, rolling, etc. The oldest classes of hammers for shingling are the "tilt," where the axis is between the point of application of the cam and the head; and the "helve-," or lift-hammer, where the hammer-block and lifting-cam are on the same side of the fulcrum. The former is used for light work, the latter for heavier work, such as shingling puddled-balls, blooming piles, etc. The modern form is the steam-hammer, employed both for shingling and welding.

Various forms of squeezers are also used, instead of the hammer, for the treatment of puddled-balls.

The rolling mill is generally used for merchant iron, the rolls being of two kinds—"roughing" rolls, and "finishing" rolls of several forms, according to the shape of the bar required.

The white-hot balls of iron formed in the puddling-furnace are taken to a hammer or squeezer, in order to expel the enclosed slag and weld the particles of iron into a compact mass, and also to confer upon the balls a shape suitable for passing through the rolls.

The Tilt-hammer, Fig. 65, rarely exceeds 5 cwts., and is not much used for shingling, except in works where small quantities are treated. It generally consists of a wooden shaft hooped with wrought iron; at one end is the head in the form of a heavy hammer, and the other end is depressed by the projecting teeth of a revolving cam, the head falling by its own weight as each tooth passes. The fulcrum is placed between the head and the cam, but nearer to the latter.

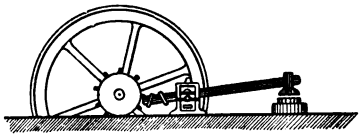


FIG. 65.

The Helve-hammer consists of a heavy mass of cast-iron weighing from 2 to 10 tons, which is lifted by projecting pieces fixed in a cam-ring, and falling by its own gravity through a space of 16 to 48 inches. Fig. 66 represents a "belly-helve" in which the cam is placed below the surface of the ground, and acts on a projection termed a "bray," which can be lengthened or shortened according to the thickness of the iron to be hammered. This form enables the workman to go round three sides of the hammer to inspect the work. The head of the arm contains the hammer face, made of wrought iron and dovetailed in. The anvil is also of wrought iron attached to a heavy casting weighing from 12 to 15 tons.

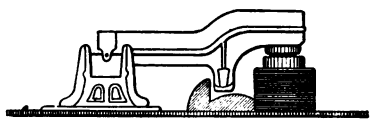


FIG. 66.

The Steam Hammer, Fig. 67, is now largely used for shingling and welding. It is a simple, direct-acting machine, and takes up little room compared with the cumbrous wheel-work of the old helve. The force of the blow in shingling is generally required to be light at first,

and with the steam hammer the force can be varied with the work to be done. Another advantage is, that the hammer always works parallel with the piece under operation, which is not the case with helves, the hammer-man having to use thickness pieces to overcome this difficulty.

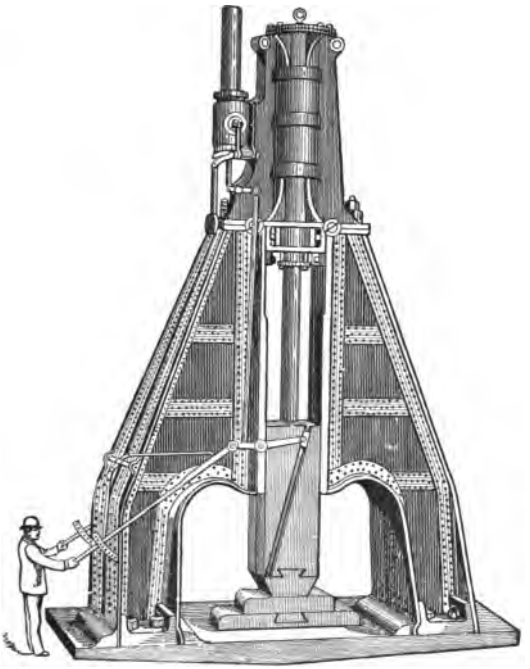


FIG. 67.

Both sides of the steam hammer are also accessible for working. It consists essentially of a vertical high-pressure engine with an inverted cylinder. The piston-rod is attached to a heavy block or "tup" moving between guides on the inner faces of the standards, which form part of a massive cast-iron framing. The ordinary hammer is double-

acting, the steam being exhausted above and below the piston. The hammer varies in weight from 30 to 60 cwts., but the force of the blow is, to a great extent, independent of the mass of the hammer head.

Squeezers.—These machines have superseded hammers in some forges, the welding of the ball being effected by

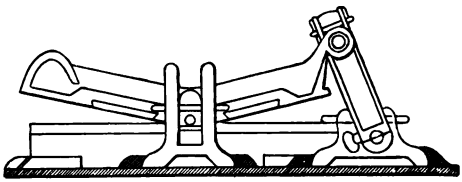


FIG. 68.

pressure without impact. There are two kinds in use—lever and rotatory squeezers.

The crocodile-squeezer (Fig. 68) is used both with single and with double jaws. The lower jaws are fixed while the upper ones are opened and closed by a crank and connecting rod attached to the end of one of them. The upper jaw is sometimes serrated so as to better grip the puddled ball, which is inserted at the wide end and gradually rolled by the workman towards the narrow end. By this means the slag is expelled and the particles of iron firmly welded.

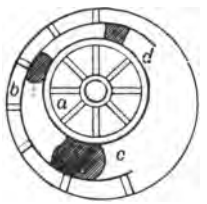


FIG. 69.

Rotatory-Squeezers.—Fig. 69 represents a horizontal machine, which consists of a revolving cylinder (*a*) having its surface corrugated, or studded with teeth. This cylinder is placed eccentrically with regard to that of the outer casing (*b*), the inside of which is similarly roughened. The ball is placed by the workman in the space (*c*) and carried forward by the rotation of the cylinder (*a*). The pathway gradually narrowing, the ball is compressed into smaller

dimensions, and finally leaves at the narrowest part (*d*) in a condition ready for rolling. The cylinder revolves at the rate of 12 revolutions per minute, and is driven by a bevel-wheel and pinion placed beneath. The distance between the pressing surfaces is fixed, so that balls of a somewhat uniform size and weight must always be used.

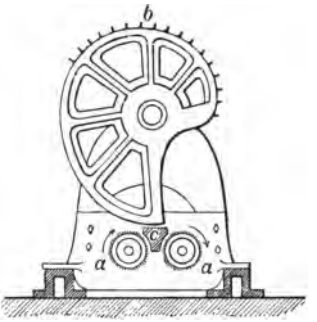


FIG. 70.

Mr. Danks introduced a vertical squeezer on the rotatory plan, Fig. 70. Two roughened parallel rolls (*a a*), 4 feet in length and 18 inches diameter, revolve in the same direction, and above these rolls, on a shaft parallel to them, is arranged a large cam (*b*), the periphery of which revolves at the same rate as the surface of the two rolls. At the end of the rolls is fixed a horizontal

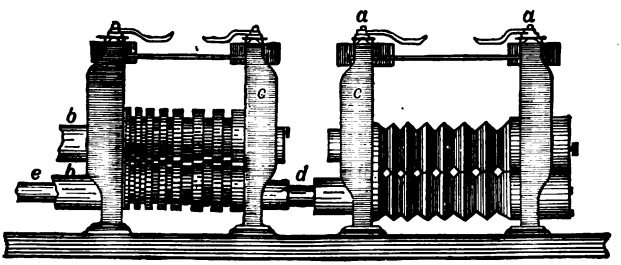


FIG. 71.

steam hammer (*c*), the face of which hammers the bloom while it is being squeezed by the cam and rolls. The bloom is then reheated and rolled.

Rolling Mill for Puddled-Iron.—The forge-train (Fig. 71) contains two sets of rolls—the roughing-rolls, represented

at the right hand, and the finishing-rolls at the left hand. The roughing-rolls are usually 5 feet long, and about 20 inches in diameter, forming a series of gothic and diamond-shaped grooves between them, diminishing in size from right to left. The larger grooves are gothic-shaped, and roughened, so as to more effectually lay hold of the iron; the smaller ones are diamond-shaped. The distance between the rolls is regulated by the screws (*a a*) and the connection between them is established by means of the cogs attached to the ends (*b b*). The "journals" or necks of the rolls run in metal bearings, which are supported in cast-iron frames or "housings" (*c c*). The finishing-rolls are arranged in housings similar to the roughing pair, but have rectangular channels instead of the diamond grooves. These channels diminish in size from right to left. The two sets of rolls are generally connected together by heavy couplings (*d e*), keyed tightly together. The two rolls of each pair revolve at the same speed, which in the roughing-rolls is about 70 revolutions per minute, and in the finishing-rolls about 90 revolutions per minute, when separate.

The bloom of iron is first passed through the largest groove of the roughing-rolls, then lifted back over the top roll, turned one quarter round, and passed through the next smaller hole. This operation is repeated until the bloom is reduced to a square bar small enough to enter the flat grooves of the finishing-rolls. In this pair, the process of reduction is continued until a puddled-bar of the desired thickness is obtained. Puddled bars may have ragged edges and a rough surface, and for the production of good bars they are cut up, piled, reheated and welded.

Rolls may be classified according to their shape and the method adopted in their production. They are generally made from a close-grained cast iron, and occasionally of steel. Plain rolls are used for sheets. Grooved rolls for

bars, rods and various sections. These rolls are required to withstand the high temperatures of the metal, and considerable wear and tear, hence they must be made of strong cast iron. For the production of sheets and plates requiring a fine surface, chilled rolls are used. They are cast in iron moulds, so as to give a hard white surface, the depth of the chill varying from $\frac{1}{2}$ to $\frac{3}{4}$ inch thick.

The "mill-rolls" or "mill-train," for rolling merchant iron, also consists of two sets; the billeting or roughing pair and the finishing pair. These rolls are provided with tightening and adjusting screws for keeping them accurately in position. In rolling small and light sections, which are difficult to keep from distortion while hot, a foreplate and guide jaws are added to the arrangement, so as to keep the sections straight. In two-high trains, revolving constantly in one direction, it is necessary to return the work over the roll after each pass, and this takes up a lot of time, so that reversing rolls are often used and reversed at each passage of the metal. The reversal is effected either by reversing the engine itself, or by the use of hydraulic friction, or other clutches and gearing on the engine shaft. For lifting the iron to the top of the single pair of rolls after a passage through them, so as to return it to the man for another passage, a travelling carriage with forked levers is used for light work. For heavy work an iron table is provided, which is raised by a single-acting engine or by a hydraulic cylinder and ram. Three-high rolls consist of roughing and finishing rolls, each of which is a combination of three rolls in its own pair of housings. In this case the mill is generally driven from the middle roll, and so arranged that the middle roll revolves forwards with the lower one and backwards with the upper one. The work thus passes backwards and forwards alternately through the upper and lower pair.

Reheating and Welding.—The bars and slabs of iron,

obtained by shingling and rolling puddled-bars, are of inferior quality, and require to be further improved, so as to form good malleable iron. This is done by cutting up the bars into short lengths, arranging them in fagots or bundles, then reheating them and hammering or rolling to any desired shape.

Bars are generally cut up by means of powerful lever shears, containing knife edges of hardened steel, termed crocodile or cropping-shears (Fig. 72). The lower blade is fixed to a cast iron stanchion, and the upper one moves on a pin (*a*) passing through the same support. The lever (*a b*) is connected with the motor by the crank (*c*). The top jaw opens and closes at every revolution of the shaft by which the power is supplied. Guillotine-shears are also used, see page 206.

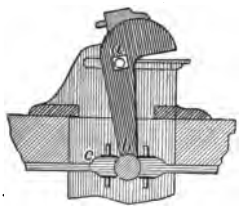


Fig. 72.

The piles or bundles, for reheating, vary greatly in size and arrangement, according to the desired size and shape of the finished bar. For ordinary bar-iron the piles are made about 2 feet long and 4 inches square. For large sizes they may be 5 or 6 feet long and 10 or 12 inches square. In all cases it is advisable to have the pieces forming the pile of uniform size. Each bundle is placed in the furnace, sometimes bound firmly together by stout wire. For common iron puddled-bars are used, but for a better quality the iron from a second rolling is used to form the top and bottom plates of the pile; if the iron, obtained from welding the latter pile, is cut up and again fagoted, the iron is termed best-best.

For iron plates, bar-iron of suitable quality is made into piles of various lengths and thicknesses, then reheated, and rolled to the desired thickness.

For large sheets, the piles are 20 inches long, 7 inches wide, and 4 inches deep, weighing about 70 lbs. The white-hot pile is made into a square bloom, by passing it through the grooves of the blooming-rolls, then through plain roughing rolls, and finally through the polished finishing-rolls.

Black-plates, as the thin plates intended for tinning are called, are doubled over upon themselves after every reheating, so that several sheets are rolled together. The plates are then cut to proper size and separated.

Nail-rods.—Two different methods are adopted for making nail-rods—by rolling a bar to the desired thinness; and by slitting a strip of iron into parallel rods, which is by far the more common. Two or three pieces of iron are made into a pile, and raised to a welding-heat in a reheating furnace. It is then taken to the rolls and extended into a bar 10 to 12 feet long and 4 inches wide; then passed between smooth rolls to obtain the desired thickness. It is then transferred to the slitting rolls (Fig. 73). These consist of spindles carrying steel discs fixed at suitable distances. When revolving, the discs on the upper spindle project into the spaces of the lower series, thus forming a rotatory shearing-machine. On inserting one end of the iron strip between the guides, it is drawn forward by the shearing-discs and cut into rods, which are afterwards cut into lengths.

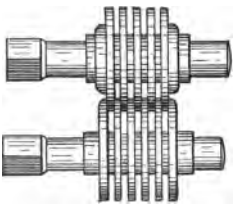


FIG. 73.

Hoop-iron is made from small piles, which are heated and rolled between grooved rolls, and finished between a pair of plain rolls, where they are pressed to the desired thickness. The great length of the bars, and their tendency to cool quickly, make it necessary to drive the grooved

rolls at a great velocity, but the finishing-rolls work at an ordinary speed of 100 revolutions per minute.

Small sizes of flat, square, and round irons are rolled with trains having three rolls in height, so as to hasten the work while the iron is hot, the mill being driven from the middle roll. The bar is passed between the bottom pair and returned between the upper pair, so that the operation is performed in both directions. A speed of 230 revolutions per minute is common. In rolling bars of small section, guides are used to keep them straight. It is usual to attach parallel guides, with friction-rollers, to the tables in front of the rolls, which are then termed "guide-mills" or "trains." In the short finishing-rolls for round iron, each has a semi-circular groove, and the two grooves when together form a complete circle.

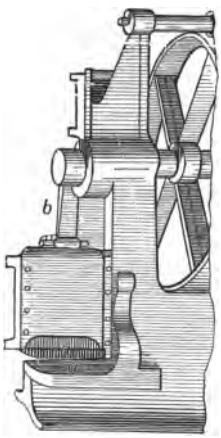


FIG. 74.

Plate-mills are usually made with two sets of rolls, each being a plain cylinder of uniform diameter. The first or roughing-pair has the top roll balanced by counterweights, whilst the top finishing-roll runs freely. These latter rolls are cast in chills and highly polished. The sizes vary from 5 to 9 feet long and from 20 to 36 inches in diameter. The speed is 25 to 40 revolutions per minute, the higher speeds being used for light plates.

Guillotine-shears.—These shears are used when a cut of considerable length is required, as in the shearing of heavy plates, sheets, etc. The form (Fig. 74) is now also used in some works, in place of the crocodile-shears, for puddled-bars, blooms, etc. It contains two diagonal-edged knife

blades (*a a*), the upper one moving vertically between guides, and worked by a crank (*b*).

Finishing.—Rails and thick bars are finished by cutting off, whilst hot, the rough or crop ends with circular saws, $3\frac{1}{2}$ to $4\frac{1}{2}$ feet in diameter, and driven at a great velocity.

The rolling-mill employed for finishing puddled iron, so as to form merchant bar, consists of two sets—the roughing and the finishing rolls. The rolls are arranged in housings with adjustments similar to those described for the forge-train, except that the finishing-rolls are provided with lateral tightening screws for keeping them always in exact position. In order to prevent lamination, the pile is passed through the roughing-rolls with the joints alternately flat and edgeways, which renders the welding uniform.

Universal Rolling-mill.—This contrivance consists of a combination of vertical and horizontal rolls, so arranged as to compress the pile equally in both directions at once. Fig. 75 shows the position of the rolls. The vertical rolls work upon slides, and can be adjusted to different distances by means of screws. The horizontal pair are driven in the usual way from the bottom roll, and the vertical pair are connected with them by an intermediate shaft, which receives its motion from the driving-pinion.

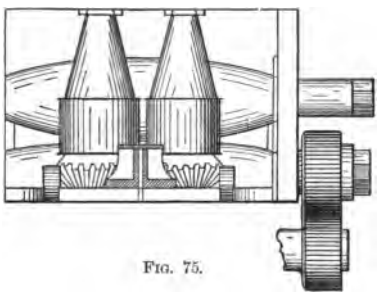


FIG. 75.

In the forging of heavy piles, steel ingots, etc., great advantage is gained by the use of a hydraulic-squeezer or press. It consists of a vertical cylinder with its ram acting downwards against a table or anvil; or a pair of dies are

used for special shapes. The ram is connected with the piston of a smaller press, by which it is raised.

Reheating Furnaces.—The bars and slabs of iron obtained by shingling and rolling puddled bars, require to be refined if the best malleable iron is desired. They are cut up into short lengths, arranged in fagots or bundles, then reheated and welded by hammering and rolling, as previously described. The ordinary reheating furnace (Fig. 76) is somewhat similar in shape to the puddling furnace; the bed is flat with a slight incline towards the fire-bridge and is lined with sand. It is essential that the fireplace should be large enough for the furnace to be rapidly raised to a white heat; the ratio of the area of the fireplace to that of the bed being about 1 : 2. The slag runs off the bed to the bottom of the flue and is termed "flue cinder." The impurities which have not been eliminated in the previous operations are largely removed in reheating and welding. The enclosed slag liquates out as a fluid acid silicate, leaving a black residue mixed with magnetic oxide, Fe_3O_4, which is removed in hammering and rolling. The basic slag in the metal acts on the manganese, silicon, phosphorus, etc., oxidising them, and the oxides pass into the slag.

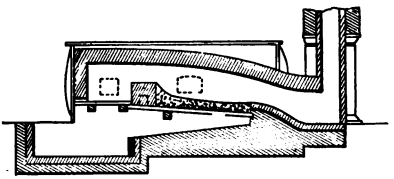


FIG. 76.

Furnaces using gaseous fuel have been largely used for reheating, such as that of Ponsard (Fig. 77). In this arrangement the gas from the producer is delivered directly to the furnace and burnt with hot air, which is heated by a "recuperator" placed beneath the furnace. The recuperator is a brick chamber, partly solid and partly hollow, contain-

ing a number of vertical passages, the adjacent ones being separated and the alternate ones connected by horizontal

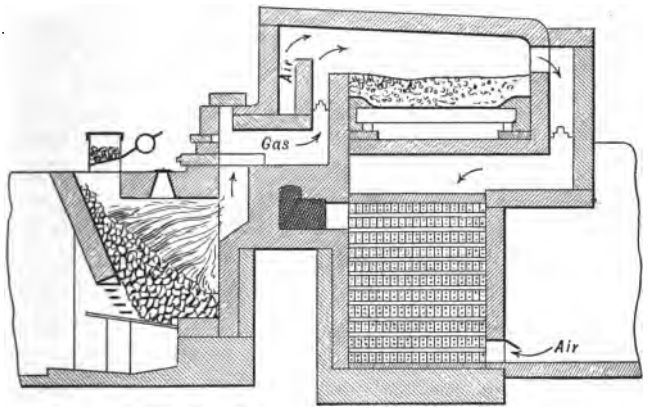


FIG. 77.

passages in the perforated bricks. The flame passes downwards, while the cold air, admitted at the bottom, passes upwards through separate channels. The action is continuous.

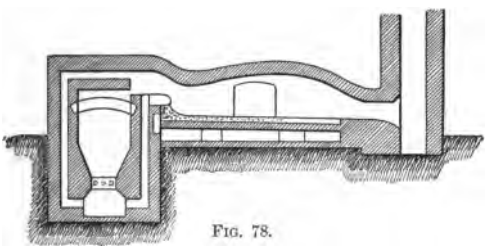


FIG. 78.

The Boëtius furnace differs from the preceding one in the manner of heating the air required for the combustion of the gas used. Fig. 78 shows the general arrangement in vertical section. The gas producer is constructed with passages in its walls, through which the air supplied to the

furnace is compelled to pass, thus being heated. It meets and mingles with the gas at the furnace bridge, where combustion takes place.

The Bicheroux furnace, working with gaseous fuel, is used both for puddling and reheating. The gas is made in an ordinary Siemens producer, built with the furnace, and burned directly, as in the Ponsard and Boëtius methods. The air for combustion is heated by contact with the bed of the furnace, a broad flat flue which runs under the bed being provided for this purpose. It is also further heated by circulating round a large vertical pipe which conveys the gas from the producer to the furnace. In a modification of this furnace, termed the Casson-Bicheroux, the walls of the producer are made with narrow channels, as in the Boëtius plan, in order to provide an additional supply of hot air.

During the reheating of iron and its conversion into merchant bar, considerable amounts of waste are necessarily made. This is due to the ragged portions having to be cropped off; the cutting of the bars and plates to size; the shearing of the edges, etc. Another source of waste is oxidation. This depends on the amount of surface exposed to the air and the draught of the furnace. For this reason gas furnaces are very useful for reheating, as a more or less non-oxidising atmosphere may be obtained.

Some reheating furnaces have been used with a basic lining instead of sand for the bottom. Pottery mine has been tried, but the loss of iron is greater, although the slag is rich in oxide of iron, and is known as "best tap." When the cinder is allowed to flow away from the iron, the furnace is said to work with a "dry" bottom. When the slag is caused to remain, and only tapped off at intervals, the furnace is said to work with a "fluid" bottom. The slag from this furnace is an acid silicate of iron, when a sand

bottom is used. Harbord & Tucker patented the use of basic slag from the Bessemer and open-hearth as a lining for reheating furnaces.

The various shapes into which the iron is finally rolled are:—plates, strips, sheets, bars, rails and various sections. Bars are round, half round, square, flat, oval, octagon, etc. Other shapes are made, such as tee-iron T; angle-iron L; channel-iron ⊔; aitch-iron H; Z-iron, etc.

There are three chief imperfections in finished iron, namely:—"Spills," which are due to enclosed foreign matter, such as slag, or oxide of iron. Such parts prevent cohesion and cause the metal to peel off after rolling; "Blisters," due to the presence of enclosed gases, such as carbonic oxide; "Ragged edges," due to imperfection in the rolls, or careless working; or it may be due to the iron being deficient in cinder, which makes the metal red-short.

COMPOSITION OF REFINING SLAGS.

	From a refinery.	From a puddling furnace.	From a re-heating furnace.
Ferric oxide (Fe_2O_3), - -	—	8·27	—
Ferrous oxide (FeO), - -	65·52	66·32	76·73
Silica (SiO_2), - - - -	25·77	7·71	16·15
Manganous oxide (MnO), -	1·57	1·29	1·51
Alumina (Al_2O_3), - - -	3·60	1·63	1·95
Lime (CaO), - - - -	0·45	3·91	—
Magnesia (MgO), - - -	1·28	0·34	—
Sulphur (S), - - - -	0·23	1·78	1·36
Phosphorus (P), - - -	1·37	—	—
Phosphoric acid (P_2O_5), - -	—	8·07	2·22
	99·79	99·32	99·92

TINNING IRON PLATES.

The plates are first thoroughly cleansed in warm dilute sulphuric acid, then washed and scrubbed with sand to remove all traces of rust, which would prevent the tin from adhering; the plates are then immersed in a bath of melted tallow, which dries them thoroughly. The tinning arrangement comprises six pots, each heated by a separate fire and termed respectively—the tinman's pot, tin pot, washing pot (divided into two compartments), grease pot, cold pot, and the list pot. The plates from the tallow or tinman's pot are placed in the tin pot, the surface of the molten tin being covered with tallow to prevent oxidation; after being heated for an hour and a half in the melted metal they are removed, drained, and plunged into the first division of the washing pot, which also contains molten tin; then taken out and brushed to remove excess of tin; afterwards they are quickly dipped in the tin in the second division to remove the brush marks. They are next transferred to the grease pot containing melted tallow, where any excess of tin is removed by draining. After about ten minutes the plates are inserted in molten tallow contained in the cold pot. Lastly, in order to remove the tin which has drained down and formed a bead at the lower edge of the plate, the edge of each plate is dipped in the list pot, which contains melted tin about $\frac{1}{4}$ inch deep; when by striking the plate sharply with a stick the superfluous metal is detached. The plates are rubbed with bran, and afterwards with sheepskin, when they are ready for use. Sometimes the plates are immersed in a pot containing fresh tin, and then passed twice through rolls in order to improve the surface.

An inferior variety of tin-plate, in which the iron is coated with an alloy of tin and lead, is termed "terne plate."

GALVANIZING.

Galvanized iron is a term applied to iron plate and iron articles coated with zinc, which prevents the iron rusting. The zinc was originally deposited by means of an electric current. It is now deposited by dipping the clean iron into a bath of molten zinc, the surface of which is covered with sal-ammoniac in order to prevent oxidation, and at the same time to remove any oxide that may be formed. The iron is cleansed in dilute sulphuric acid before dipping it in the molten zinc.

CHAPTER XIV.

IRON-FOUNDING.

THE art of founding, although not strictly a modern process, is one that has been greatly developed of late years. The caster generally works from a pattern, an impression of which is made in sand, or other suitable material. The moulding material must possess considerable pliability, be non-fusible, and unalterable in composition, so as to lend itself readily to the making of moulds, into which the fluid metal is poured, thus obtaining an exact fac-simile of the pattern, and, while forming a resisting surface, should be sufficiently porous to allow the liberated gases to escape.

The pattern is made larger than the desired object, about $\frac{1}{16}$ to $\frac{1}{8}$th of an inch to the foot being allowed for the shrinkage of the cast-iron, varying with the kind of iron and the articles to be cast. When a pattern is required for a standard article from which castings will often be required, mahogany is preferred on account of its durability; in other cases pine is generally used. Most patterns are coated with shellac-varnish so as to present a hard surface, and to close up the pores of the wood, thus rendering it impervious to moisture, which might so distort the pattern as to render it useless. It also imparts a smooth surface,

so that the sand has less tendency to stick to the pattern when it is withdrawn from the mould.

The pattern often requires to be modified from what the casting is to be, in order to render the moulding practicable. For instance, castings which require to have recesses left in them necessitate the use of a piece of wood called a "print." This is placed on the pattern, which, when it is withdrawn, leaves a space for the core to rest on, and a core-box is made to furnish a suitable core, the ends of which can be placed in the impression left by the print.

Pig Iron Used.—A mixture of different kinds of pig iron is generally preferable to any single brand, because the metal casts more solid. Further, as cast-iron articles are required of different degrees of hardness and strength, according to the purposes for which they are required, it is difficult to get the requisite quality without mixture. A slightly-mottled fine-grained pig iron is suitable for castings where great strength is required, and a whiter variety offers a great resistance to a crushing force, while a greyer iron is weaker. The different kinds of grey iron have a tendency to become whiter when remelted, owing to some of the carbon passing into the combined form; this produces a slightly-mottled cast-iron when a small-grained grey pig is used. It sometimes happens that the reverse is the case, and a softer iron is then obtained.

The condition of the carbon is modified by a variety of circumstances, such as the mode of melting, the rate of cooling, and the presence of impurities. It has been already stated, that quick cooling tends to increase the amount of combined carbon, and slow cooling to increase the amount of free carbon. Manganese, phosphorus, and sulphur, in notable quantity, cause white iron to be formed, while silicon acts in the opposite way, causing the separation of graphite. When a number of foreign elements are present,

they modify the effect which each would have on the iron when present alone.

Grey iron is most generally employed, because it has the property of becoming thinly liquid when melted, and of expanding when on the point of solidifying, which makes it particularly suitable for foundry work. Prof. Turner has shown that silicon when added to white iron, produces a soft grey iron by the separation of graphite and when present in suitable proportion improves the quality of the metal. From his experiments he deduces the following:

1. "White pig iron contains less than 1 per cent of silicon, but when sulphur, or manganese is present the iron may still be white, although more than 1 per cent. of silicon is present."

2. "Mottled iron contains about 1 per cent. of silicon, and a small proportion of sulphur considerably affects the product."

3. "In grey iron almost the whole of the carbon is graphitic, and it usually contains about 1·8 per cent. of silicon, the maximum limit being 3 per cent."

In addition to pig iron the founder adds scrap cast-iron to the melting charge for most purposes. This scrap consists of gates, runners, heads, etc., and worn-out and waste castings of all kinds. The larger the amount of scrap to be used, the softer should be the pig iron melted with it. Scrap, however, unless its composition is known, obviously cannot be much used where exact and definite mixtures are required.

The nature of the fractured surface is generally the only guide the founder employs as to quality. But it is necessary to know the composition by analysis if the operator is to have a sure guide. Mr. Buchanan gives the following table to show the uncertainty of composition of what is sold as No. 3 pig iron of one brand:

	I.	II.	III.	IV.	V.	VI.
Silicon, - - -	3·340	3·360	2·240	2·800	2·900	2·710
Phosphorus, - -	1·110	0·900	1·580	1·550	1·560	1·640
Sulphur, - - -	0·016	0·014	0·045	0·032	0·037	0·031
Manganese, - -	0·410	0·362	0·274	0·280	0·310	0·340
Combined carbon, -	0·581	0·496	0·245	0·026	0·152	0·070
Graphite, - - -	3·440	2·460	3·500	2·740	3·400	2·950
Total carbon, - -	4·021	2·956	3·745	2·766	3·552	3·020

Scrap iron is mixed with a foundry charge, and such scrap should be kept separate as far as possible so that its approximate composition may be known. Mixed scrap of unknown composition is a source of danger to good cast-iron. Heavy machinery scrap may be assumed to contain about 1·8 per cent. of silicon, 0·8 phosphorus, and 0·11 of sulphur. Light scrap may contain about 2 per cent. of silicon, 1·2 of phosphorus, and 0·11 of sulphur.

The tensile strength of pig iron varies from 4 to 10 tons per square inch, the average being about $7\frac{1}{2}$ tons. The crushing strength should bear a proportion to the tensile strength of 4 to 1. When the ratio is much less than this, the metal is weak; and when the ratio exceeds that of 6 to 1, the metal is hard and brittle.

Influence of Remelting.—When cast-iron is remelted it becomes harder and closer in texture. Owing to the

	Charcoal Pig Iron.	First Remelt.	Second Remelt.	Third Remelt.	Fourth Remelt.
Total carbon, -	3·940	4·100	4·300	4·470	4·680
Graphite, - -	3·060	2·900	2·420	2·900	2·670
Combined carbon,	0·880	1·200	1·900	1·570	2·010
Silicon, - - -	0·820	0·750	0·630	0·660	0·570
Sulphur, - -	0·020	0·030	0·040	0·040	0·045
Manganese, - -	0·780	0·660	0·530	0·310	—
Phosphorus, - -	0·232	0·248	0·274	0·237	0·245
Specific gravity, -	7·010	7·300	7·350	7·400	7·470

oxidising effect the silicon and manganese diminish, while the phosphorus and sulphur increase by concentration. This is well shown in the analysis by West at the foot of the previous page.

The total carbon has increased by taking up carbon from the fuel. The amount of carbon existing as graphite has diminished, while the combined carbon has increased, which explains the increase in hardness.

Defects in Castings.—Faulty castings may be due to the use of unsuitable pig iron and scrap, while two important parts are played in casting by the character of the fuel and limestone, and the way the fusion is effected. The casting ladle should be coated with one-third of clay and two-thirds of lean sand, these components being mixed with about double their volume of horse dung. After this is dried the whole is blackened. The blacking mixture consists of one part graphite, one-half part dry clay, and one-half part of ground-up pots. In some works the larger ladles are lined with thin fire bricks. To prevent the iron chilling in the ladle the metal is covered with ground coke or charcoal.[1]

Allowing the metal to stand in the ladle has a good effect on its character. The absorbed gases escape, and the manganese and silicon present act on the dissolved oxide of iron, forming silicate of manganese, which passes into the slag. The dissolved carbon acts in a similar manner, carbonic oxide being formed. Manganese also acts on the sulphur present, forming sulphide of manganese, which rises to the surface. The hotter the metal the more perfect these reactions. Additions are frequently added to the metal in the ladle to remove dissolved gases and oxides. Some of these additions act mechanically, such as lead, zinc, and tin, by bringing impurities to the surface. Stirring the metal

[1] *Stahl und Eisen*, vol. xx., p. 1041.

has the same effect. Others are added to act chemically. Aluminium is the chief of these. It is added in the form of ferro-aluminium or as pure metal, in quantities amounting from 0·02 to 0·05 per cent. Aluminium decomposes dissolved oxides, forming alumina, which passes into the slag. When the metal is about to be poured, it is scraped clean, and some dry moulding sand is thrown on the surface, which produces a thin coherent slag.

Blow-holes are due to damp sand, defective cores, improper venting, and small or incorrectly placed risers or gates. The extraction of cores through small openings often leads to breakage of the casting. Another defect in castings is due to dirt or impurities, caused by the washing away or breakage of the mould. Badly fitting cores, insufficient heat, too few or too small runners, and shortage of metal are causes of defects.

In remelting pig iron for foundry purposes two kinds of furnaces are employed—Reverberatory-furnaces and Cupola-furnaces.

The Reverberatory-furnace (Fig. 79) varies in size according to the work required, and has a capacity of from 3 to 10 tons. The charging doors are on one side and the tap hole on the other. It is used for melting iron for casting large pieces, and for remelting large faulty castings. The large volume of air passing over the bed has a refining influence on the molten iron, oxidising some of the silicon, phosphorus, etc. This furnace is said to produce a tougher and more homogeneous product than the blast furnace. On

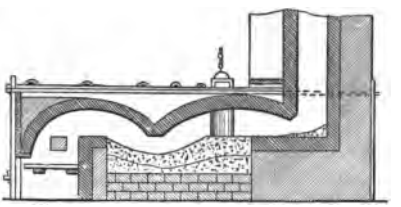


FIG. 79.

the other hand, more iron is oxidised and wasted in the slag, and more fuel is consumed. This furnace is also used when it is desired to melt the iron out of contact with the fuel, so as to prevent any impurities in the latter from uniting with the iron.

The Cupola-furnace generally employed for foundry purposes has a cylindrical hearth, and tapers somewhat towards the top; it differs from a smelting blast-furnace in the absence of boshes. Coke-furnaces generally have a closed front wall with no fore-hearth, the metal being removed at one tapping. Charcoal-furnaces are often narrower at the top and bottom than in the middle. They often have a fore-hearth, which enables the furnace to contain more iron. The flux employed is principally limestone, which forms a slag with the ash of the coke, the sand adhering to the pigs, and with parts of the furnace lining. Some founders add fluor-spar, which produces a more liquid slag. The waste heat of cupolas has been utilised with some furnaces for heating the blast, thus effecting an economy of fuel. If, however, too high a temperature be employed the thinly liquid slag rapidly attacks the lining. If too low a temperature be used, the iron becomes too pasty, and the slag forms a nose on the twyers. The blast is usually supplied by a fan.

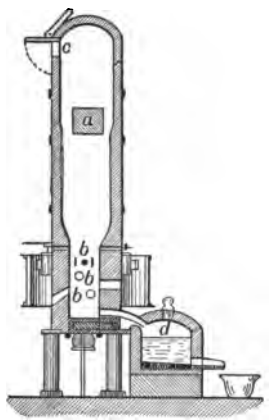


FIG. 80.

An improved form of cupola has been invented by Mr. Stewart. Fig. 80 represents a vertical section. The charge is introduced at the door (*a*) from a landing-stage not shown

in the figure. The twyers are arranged at three different levels (*bbb*), so that there are three zones of fusion, thus distributing the blast and causing a more perfect combustion. The cupola is arched at the top, and is provided with an opening (*c*) for the escape of gases. The furnace is supported on four pillars and is provided with a drop bottom. A receiver (*d*) is fixed in front for the molten metal, from which it is tapped into the casting-ladle. The blast is provided by a Root's blower (Fig. 81).

This machine consists of a pair of 8-shaped revolvers (*aa*) enclosed in an iron case. These revolvers ars mounted on steel spindles, working in gun-metal bearings in the ends of the case, and coupled outside by means of a pair of toothed wheels, so as to control the position of the pieces with regard to each other. The blower is driven by means of two leather belts, one crossed and the other open, working on pulleys at opposite ends of the respective spindles. The air-inlet as a rule is at *A* and the outlet at *B*, but in special cases the direction may be reversed. By means of this blower a pressure of blast is said to be procured, far in excess of that attainable with a fan, and with less expenditure of power.

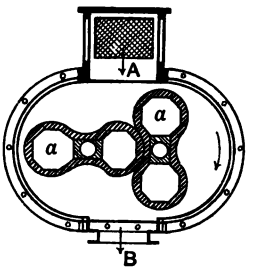


FIG. 81.

In the case of heavy castings, requiring several tons of metal, a common plan is to melt about two tons of iron in a cupola, and tap it into a ladle. Then to close the tap hole, and melt another two tons, which require about half an hour, then to run the metal into the ladle containing the first charge. This may be repeated three or four times, until the requisite quantity of iron for the casting is obtained.

The metal from each tapping is covered with charcoal, about an inch thick, to diminish the loss of heat; and the excess of heat imparted by each addition of metal to the ladle is sufficient to keep the whole in a molten condition for upwards of three hours.

There is a common idea that the contraction of a cupola at the twyers is primarily intended to reduce the quantity of coke necessary to form the bed for the first charge; but while that is so, the chief purpose is to get the blast right to the centre of the cupola. In lining a cupola, and afterwards fettling it, care must be taken that the change from the smaller to the larger diameter is made gradually. For successful working, the slag, as it drops away from the blast zone, must retain its fluidity. The reduction in diameter is equivalent to a lengthening of the twyers towards the centre of the furnace, and thus producing intense combustion, beginning 4 to 6 inches above the top twyers, if two or more rows of twyers be in use, and extending over all the circular area of the furnace A double row of twyers gives the necessary twyer area for the entrance of the blast, and the metal will thus melt more quickly. The higher twyers supply the necessary oxygen for the combustion of the carbon monoxide generated below.[1]

The melting zone of a 36-inch cupola, with two rows of twyers, and a blast pressure of 8 ounces, begins at 6 to 8 inches above the upper twyers, extending vertically for about 24 inches, and then terminating abruptly. Three rows of twyers cause a rapid melting, but the top row cuts up the lining badly, and necessitates a deep bed of coke. The appearance of the flame at the charging door is a guide as to the proper working of the furnace. The total twyer area is regulated by the diameter of the cupola, the blast pressure available, and the density of the coke.

[1] Buchanan, South Staff. Iron and Steel Inst. 1901.

Cupolas are liable to scaffolds, due to the charge becoming wedged in the middle of the furnace through a deficiency of flux. The slag is then pasty, and when it reaches the twyers tends to solidify. Light coke with high percentage of ash also causes scaffolds. To avoid scaffolds, a sufficiency of flux, usually limestone, and a good coke with a high calorific power are required. A cupola with a fore-hearth takes more fettling, burns more fuel, but gives a metal more perfectly mixed.

Moulding and Casting.—The founder distinguishes iron castings as:—open-sand, green-sand, dry-sand, loam, and chilled casting, according to the nature of the mould employed. Occasionally a complex piece may embrace two or more methods. For the sake of simplicity, open-sand has been distinguished from green-sand moulding, but strictly speaking, green-sand may be divided into "open sand," "bedding in," and "rolling over." In a following paragraph rolling over is described as green-sand moulding, but the latter is not always of necessity "rolling over."

Open-sand.—This method is employed where finish is of secondary importance, the castings, as a rule, presenting a rough surface on the top side, due to the irregular setting of the molten metal, together with particles of slag and sand washed off the sides of the runner. The castings made in open-sand are generally to be used in contact with masonry or earth work, such as foundation plates, or washers, frames, etc. Firebars for the grates of boilers are generally cast in open sand, and as the rough portions are in contact with the fuel a smooth surface is unnecessary. The method adopted for preparing the mould is as follows:—On the floor of the foundry the moulder makes a bed, varying with the size of the pattern, by digging out the sand and treading the bottom firmly. He then places two straight-edges across the bed and by means of a spirit-level and a third

straight-edge makes the two former ones level crosswise and lengthwise, this acting as a guide for the surface level. He then fills in the bed with black sand, slightly damped, and passed through a riddle to free it from any lumps. The bed is then rammed with a flat rammer and the superfluous sand strickled off. By means of a trowel a portion of the sand is removed to make room for the pattern. The latter is placed in position and rapped or tapped with a mallet until the surface coincides with the flat surface of the bed. After ramming in the pattern, additional sand is added to make up the walls of the mould which have been depressed by the ramming.

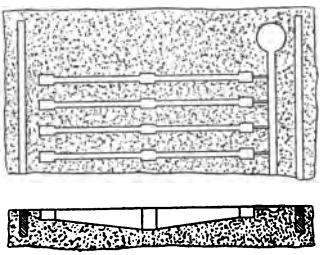


FIG. 82.

After making a series of moulds in the prepared bed, a long groove or channel is made, and also smaller ones connecting each mould with it, which are used for running the metal to the moulds. The metal is generally poured into a basin-shaped cavity made in the sand which serves as a reservoir to feed the main and subsidiary runners. Fig. 82 will serve to illustrate this method of casting.

Green-sand.—What is termed green sand has no reference to the colour, which is black, due to admixture with coal dust. It is really raw or new sand. Green-sand castings form the largest group in foundry practice, such as machine and engine parts, tools, etc. New sand is not used alone in the raw state, but is mixed with one part of old or used sand, and one part of coal dust. The mixture is then well kneaded in a mill, and water added if it is too dry. After about twenty minutes the operator tests the sand by

squeezing it in his hand, and if it retains its shape, without undue crumbling, it is said to be tough. This is in some foundries put through a mechanical sieve before being used for moulding. The sand in this condition is known as facing sand, and is used to form the walls of the mould next to the pattern.

Suppose it is desired to make a mould for a flange, as shown in plan and section in Fig. 83. The method may be started in one of several ways; for instance, a flat board with two battens across may be employed, the pattern laid on, with the larger surface downwards, and then a cast iron box-part placed on the board. Or instead of the board a temporary box-part may be used, rammed *with sand*, and this would constitute an "odd-side." A dust bag, containing powdered brick dust or charcoal is shaken over the pattern to prevent the sand clinging to it. Facing sand is now put round the pattern and the box filled with old sand, then it is well rammed down and the surface strickled off level with the walls of the box. It is then inverted and the board laid aside. Another box-part is placed on the top and either brick dust or baked sand shaken over the whole surface. Two taper wooden pegs are placed one on either side of the pattern, sand added and rammed in, and the pegs withdrawn, leaving two taper holes. One, through which the metal is poured is termed a "gate," the other, to carry away any loose particles, is called a "riser." The box-part put on last is then taken off and the pattern rapped to loosen it, when it is carefully removed. A wire,

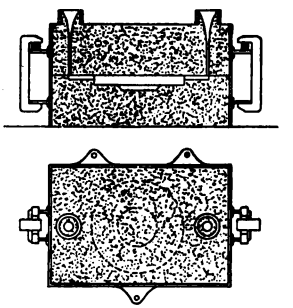


FIG. 83

termed a vent-wire is pushed through the bottom to allow of the escape of gases. The mould is dusted with charcoal and the loose particles blown off by hand bellows.

The loose parts are then finally put together and well clamped or weighted. On the top box-part, where the two holes are made, are placed two rings of cast iron, about 3 or 4 inches in diameter; and these, after being rammed with sand and a cone formed inside, serve to give an additional head of metal, which exerts a pressure on the whole of the enclosed mass. It is advisable to cover these holes with paper previous to putting on the rings, so as to prevent any loose particles falling into the mould. The paper readily burns away when the metal comes in contact with it.

Core-making.—Cores may be divided into two groups (*a*) green sand; (*b*) loam. The former is made from the facing sand already described, the latter is made from a mixture of new sand, clay or marl, and stable refuse; the mass is worked in the sand mill and thoroughly mixed, the straw gives a binding effect as well as increasing the porosity of the mass, which facilitates the escape of the gases. Whether working in loam or green sand the method of proceedure is the same. The sand is rammed into boxes (core boxes), which take to pieces, as it would otherwise be impossible in some cases to remove the core when it is made, due to protuberances. Rods or nails are included in the cores, which act as strengthening bars to resist the weight of metal. When the core is withdrawn from the box it is placed in a stove for about 8 to 12 hours. The cores are coated over in some instances with blacking (a mixture of plumbago and water), after partial stoving, then allowed to thoroughly dry. The object of stoving is not only to harden the mass, but is a means of safety; the water being driven off by stoving, since, if it were allowed to remain and come in contact

with the molten metal in the mould, the steam generated would cause damage to and, in some cases, destruction of the mould.

Dry-sand.—This method is employed chiefly for large castings where green-sand would not sufficiently resist the pressure applied, and for ornamental work, such as parts of machinery, long tubes, statues, etc. The moulding material used is a mixture of black foundry sand and fresh sand. The process of moulding is the same as with green-sand, but when the moulds are finished they are dried in a stove from 12 to 24 hours and then blackened. The metal is then poured in the usual way.

Loam.—This branch of moulding differs from the preceding ones, in the use of a clayey-sand termed "loam," and in not generally using a pattern to form the mould. The loam is formed of a mixture of sand, clay, and cow-hair moistened with water. Take the case of an ordinary round evaporating pan. A board (*a*), Fig. 84, is first made and attached to a spindle (*c*) to form the inside, and a similar board (*b*) to form the outside diameter and shape. These are termed strickle-boards. This method of strickle-moulding is often employed also in green and dry sand work.

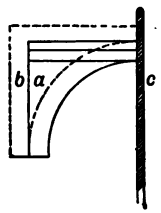


FIG. 84.

The mould is commenced at the bottom of a pit, by making a foundation formed of a layer of bricks, and then covering it with loam. A flat plate or ring of iron is placed level on the loam, and in the centre is fixed the iron spindle (*c*), the lower part of which is turned slightly conical, fitting into a bored bush with arms or feet attached; this is rammed in the floor, or attached to the base plate of the mould. The top part of the spindle is kept in position by a hole in a plank laid across the mouth of the

pit. The board (*a*) is now swept round and another layer of bricks and loam added, and so on until a space is filled up of the size and shape of the interior of the pan, which is generally cast bottom upwards. For large work the moulder leaves a space round the spindle, in which a fire is suspended in a grate for drying the loam, after removing the spindle and board. In some cases it is dried in portions as it is built up. After blacking the core, the loam is struck up by the board (*b*), which leaves a coating of loam exactly the thickness of the metal afterwards forming the pan. A cope or cover corresponding to the top flask of an ordinary sand-mould has now to be made. This may be built up in bricks and loam in the same way as the interior, and dried and blackened on removal; or a sand top-part may be rammed around the thickness contained in a flask or box. In either case, the top is lifted when the operation is completed, and the thickness formed by the board, removed. The top, after drying and blacking, is then lowered into place again. The whole is placed in a pit and well rammed all around with sand, in order to prevent rupture or distortion of the mould when the metal is run in.

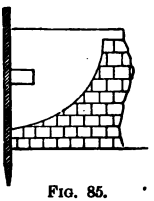


FIG. 85.

The mould and casting are left to cool for a certain period, depending on the size of the article. In some cases, portions of the core have to be removed immediately the metal has solidified in order to prevent the casting splitting by contraction.

Some founders, instead of striking up the thickness on the core, and subsequently moulding the cover, strike the outside of the pan direct, on an independent plate, the board being made in this case the reverse way, as in Fig. 85. This outside, after drying and blacking, is placed in the pit and the inverted core lowered into it. This plan

is particularly advantageous in cases where the bottom of the pan has to withstand great heat when in use, since the casting will be sounder at the bottom, because of the sullage, etc., rising to the top part of the mould.

Casting in Chills.—This process may be illustrated by a brief description of the method employed for casting chilled-rolls. Such rolls must have a close grain, and a hard, smooth, highly polished surface.

The mould is made up of a combination of sand and cast-iron. The parts, intended to form the bearing and driving or tenon-ends, are moulded in a strong sand, then thoroughly dried, and coated with blacking. The mould, for the working-part or barrel of the roll, is formed of a heavy cylindrical casting of iron, truly bored out to a size sufficient to allow of the roll being turned to the proper dimensions. The sand-moulds are secured to this casting by means of cotter-pins, and the whole is then placed vertically in a casting-pit. The iron, after melting in a reverberatory furnace, is run in by a gate formed in the bottom box, and enters the lower bearing in a tangential direction, so that the molten metal is caused to rotate rapidly, forcing the dirt and slag to the centre of the mould, as the centrifugal action of the spinning metal causes the heavier and purer particles of iron to fly towards the outside, while the lighter particles, being kept inwards, flow out through the head. This rotatory action greatly diminishes the liability to pin-holes. The metal, after filling the mould, rises to the top into a supplementary channel called the "head," where the dross or "sullage" is collected. This opening also serves the purpose of feeding the casting with fresh iron as the various parts set and contract.

The effect of using the iron cylinder as a mould, is to cause the iron to solidify rapidly in contact with the walls of the "chill-mould," in consequence of the heat being

rapidly conducted away. The depth of the chilled surface is made to vary, according to the purpose for which the casting is required, and can be regulated by mixing various pig irons in the proper proportion, and then testing the iron by means of test pieces, of uniform size, cast in chill-moulds. By fracturing these tests, the depth of the chill is ascertained and the right mixture determined. Pin-holes and split-castings are caused in various ways, such as by injudicious mixing of unsuitable pig irons, porous chill-moulds, bad melting, pouring too hot or too cold, etc.

CHAPTER XV.

STEEL.

STEEL is a malleable and tough alloy of iron with carbon, the latter not exceeding 1·8 per cent., and which in the cast or wrought state is malleable, ductile, forgeable, and weldable. Unless kept at a very high temperature for a prolonged period, the carbon is wholly in the combined form, and therefore the metal contains no graphite. When the carbon in steel exceeds about 0·25 per cent., it can be hardened and tempered. This definition does not apply to special alloys of iron with elements other than carbon, such as manganese, nickel, etc. But while the carbon is the dominating element, other constituents are invariably present, either as impurities, or purposely added to impart special properties. Before the advent of "mild-steel" the term steel had a very definite and clearly defined meaning in the minds of practical men, inasmuch as it was considered to be a combination of iron with sufficient carbon to enable it to be hardened by a sudden quenching from a red heat, and again softened by raising it to a strong red heat and allowing it to cool slowly. The introduction of the Bessemer and Siemens' processes of steel making offered facilities for the manufacture of metal containing much less carbon than that

obtained by the older methods, and eventually products were obtained with carbon contents as low as 0·05 per cent. Now as such metal is quite incapable of being hardened in the usual way, the original definition of steel obviously would not apply to it, and the term "mild-steel" was invented to express those varieties that contain less than about 0 25 per cent. of carbon. It will be thus seen, that while the new term has a definite meaning, namely, iron-carbon alloys that cannot be hardened in the usual way, the application of the term steel to such metal is unfortunate, as it tends to confuse the significance of the term steel, that in its specific sense had such a clearly fixed meaning. In addition to carbon, there may also be present secondary alloys of iron with nickel, chromium, tungsten, manganese, molybdenum, copper, aluminium, etc. The above-mentioned properties, characteristic of steel, may be present in metal produced in very different ways. If the steel has been melted and cast into moulds it is practically free from slag. If it has been manufactured by weld and wrought methods it contains enclosed slag. These two varieties of iron and steel may be exactly expressed by the terms "ingot" and "weld" metal respectively. The presence or absence of slag therefore affords a valuable basis for discrimination between ingot and weld metal, and the power of being rendered hard by sudden quenching, or soft and tough by slow cooling, should be the test of steel.

Sir Joseph Whitworth proposed to distinguish between iron and steel by the use of a numerical coefficient, representing the sum of the tensile strength of the metal in tons per square inch of cross section, and the figure representing the percentage of its elongation before fracture, in a standard length of test-piece. Gautier, Holley and others comprehend under the term steel all alloys of iron and

carbon that have been cast into malleable masses. Now, cast iron is also an alloy of iron and carbon, and although it has been melted and cast into moulds, it is wanting in malleability. Further, although it can be hardened by sudden quenching, it cannot be tempered so as to impart that flexibility and freedom from brittleness as in the case of steel. There is, however, no strict line of demarcation between steel and cast iron, for as the carbon is gradually increased the steel gradually loses its toughness and malleability, and approximates to that of cast iron. Moreover, cast iron is generally a much more impure metal than steel, and these contained impurities are a determinating cause in the properties of cast iron, for when steel contains similar impurities it becomes hard and brittle, like cast iron.

According to these views the following scheme will express this mode of classification for ordinary varieties:

	Malleable.		Non-Malleable, except after a Cementation Annealing.
	Cannot be hardened by sudden cooling. Iron.	Can be hardened by sudden cooling. Steel.	
Cast when molten into a malleable mass, -	Ingot Iron	Ingot Steel	Cast Iron
Aggregated from pasty particles without subsequent fusion, - -	Weld Iron	Weld Steel	—

Structure of Steel.—There appears to be a close analogy between the structure of alloys and impure metals and that of igneous rocks. In considering the history of a rock it is necessary to bear in mind that two distinct questions are involved:—(1) the origin of the minerals of which the rock is composed; (2) the origin of the rock itself. In some cases there is an intimate relation

between the origin of the rock and that of the minerals that enter into its composition. In some cases the minerals have crystallised *in situ*, and in other cases the origin of the minerals is distinct from that of the rock. Now just as a rock is made up of distinct compounds, termed minerals, so steel may be composed of two or more bodies, each having a composition differing from that of the whole mass. These component bodies, having a well-defined constitution, and in many cases a characteristic structure, have also definite freezing points, and appear to have a separate existence, although their action is limited by being engulphed in the general mass. Such bodies must therefore exert an influence on the properties of the main mass, and in some cases this influence is the dominating one. Now in the case of impure metals and alloys, the subsidiary or component bodies are always formed *in situ*, and therefore bear an intimate relation to the main alloy, of which they are the offspring. Further, a rock when slowly cooled from a molten magma, affords opportunities for minerals to form, to crystallise, and become more and more separate, the length of time determining the size of the crystals; but when the molten rock is cooled very rapidly it assumes a glassy or amorphous structure. Very much the same thing occurs in the cooling of alloys.

Howe[1] considers steel to consist (*a*) of a matrix of iron, which is sometimes (as in ingot iron and annealed steel) practically pure, and sometimes (as in hardened steel, manganese steel, etc.) chemically combined with a portion, or even the whole of the other elements that are present, probably in indefinite ratios, its mechanical properties being greatly affected by them; and (*b*) of a number of independent entities, which we may style "minerals," chemical compounds of the elements present, including iron, which

[1] *Metallurgy of Steel*, p. 2.

crystallise within the matrix, and by their mechanical properties, shape, size, and mode of distribution, also profoundly affect the mechanical properties of the composite mass, though probably less profoundly than do changes of corresponding magnitude in the composition of the matrix.

Steel and cast iron may be termed alloys of iron and carbon, etc., and have a close analogy to that class of indefinite compounds, termed solutions. Now an alloy of two elements in the liquid state may be either that of (1) a solution of one metal in another; (2) a chemical combination; (3) a mechanical mixture; (4) a solution or mixture of two or of all of the above; and that similar differences may obtain as to its condition in the solid state. A solution therefore need not be a liquid, but that in certain solids, especially when they are at a high temperature, an added element tends to diffuse itself uniformly through the mass, from which, as from a liquid solution, it may be crystallised out on cooling. White hot steel is such a solution. A mass may be solid and yet retain many of the characteristics of a solution. Rothmund has shown, for instance, that molecular changes have precisely the same effect in producing crystallisation from a solid solution that the freezing of an ordinary solution has. Just as a body dissolved in water is separated by freezing, so a body dissolved in a solid may "fall out" when a molecular change takes place. Hence the molecular changes of iron are of the first importance in relation to the solution theory of solidified carburised iron.

As before stated, an alloy may be compared to a rock, which contains different constituents, all of which may be united in the liquid condition, but separate on cooling, forming two or more alloys of different densities and of different fusibilities. A solidifying steel ingot acts in a similar way, for we find that the chemical condition of the

components of the solidified steel, and the shape and arrangement of its individual crystals are probably affected by changes in its ultimate composition and by the conditions which precede and accompany its solidification and cooling.

Take the case of a highly carburised steel. If it be long exposed to a certain high temperature while cooling, graphite crystallises out as a distinct body. If the steel be cooled with sufficient rapidity from the molten state, no graphite is formed, but the whole of the carbon passes into the state that makes the steel hard and brittle. If the steel is cooled slowly from a red heat most of the carbon forms the definite carbide, Fe_3C, which, distributed uniformly in minute crystals through the matrix of iron, strengthens and hardens the mass, but much less than does the carbon when in the condition induced by sudden cooling.

Solution Theory.—The solution theory of carburised iron affirms that this substance is, when fluid, a solution of carbon in iron, and that under certain conditions, the solidified mass also forms a solid solution. It further affirms that these liquid and solid solutions obey the ordinary laws of solution, which have been widely studied in the case of aqueous, saline, and organic solutions. The experimental data which enable the theory to be applied are mainly afforded by means of the pyrometer and microscope, used in conjunction with chemical analysis.

This kind of work has been admirably done by Roberts-Austen, who, in his fifth report to the Alloys Research Committee of the Institute of Mechanical Engineers,[1] showed the close analogy between a solution of common salt in water and that of carbon in iron. A thermometer is placed in a solution of salt in water while the liquid is caused gradually to cool, and the temperature at which the first crystals are formed is noted. It will be observed that only

[1] *Engineering*, Feb. 17, 1899.

a portion of the liquid solidifies at that temperature, and the remaining liquid requires to be cooled down to a much lower degree before it solidifies. It will be further noted that this residual liquid wholly solidifies at one point.

Now take a solution of 10 per cent. of salt in water and cause it gradually to cool by means of a freezing mixture. The whole will remain liquid till $-8°$ C is registered, when pure ice will crystallise out. When this has been effected, the temperature will gradually fall until a temperature of $-22°$ C. is reached, when the remaining liquid freezes. The composition is then found to contain 23·5 per cent. of salt. This is the "cryohydrate" or "eutectic" of ice and salt, and consists of a mixture of ice and salt in intimate juxtaposition, as is usually the case with eutectics. Now take a solution of 25 per cent. salt and allow it to cool as in the previous experiment. In this case the first solid to separate is pure salt, which takes place at $-12°$ C. leaving the eutectic mixture still liquid, which is invariably found to be of the same composition as before, and to freeze at $-22°$ C. The freezing point curve of ice and salt consists of two branches, with one eutectic or mixture of minimum fusion.

The case of carburised iron is very similar. The freezing point of pure iron is taken as 1600° C. Carbon will dissolve in iron in much the same way as salt in water. Mr. Stead prefers to look upon the dissolution of carbon in iron as analogous to that of sodium oxide in water. In this case the oxide first combines with the water to form a definite hydrate, and this afterwards dissolves in the water like salt. In like manner he considers that carbon first forms a definite compound or compounds, and these then dissolve in the iron like salt does in water, for it is difficult to see how carbon, which has a chemical attraction for iron, can dissolve in iron and yet not be in chemical combination with it.

The diagram (Fig. 86)[1] embodies the information gained from a large number of cooling curves of carburised iron, which have been obtained by Roberts-Austen by means of his automatic recording pyrometer. It indicates, for each percentage of carbon, the temperatures at which evolutions of heat would occur in a slowly cooling liquid mass. The curve has two main branches, AB and BD, meeting in B, at the

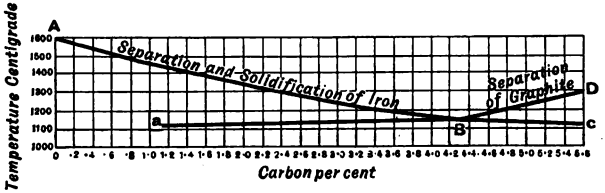


FIG. 86.

horizontal line ac. The line AB corresponds to the separation of pure ice, as explained above, and the line BD to the separation of pure salt. The line BD denotes the separation of graphite, while the line AB indicates the freezing of iron. There is, however, this difference between the ice and the iron: the latter, on account of the high temperature at which it melts, still retains a certain amount of carbon after it has become solid. Hence there is a solid solution of iron and carbon, and this introduces further complications when the iron has cooled to a temperature at which it is no longer capable of retaining dissolved carbon.

A solution of carbon in iron, like salt in water, may be saturated or under-saturated. If the solution is weak, or as it may be termed, dilute, the first solid to separate is either pure iron, or a solid solution of carbon in iron, containing, however, less carbon than the solution from which it solidified.

[1] *Engineering*, Feb. 17, 1899.

The residual, mother liquor, from which either the graphite or the iron is separating, becomes correspondingly poorer or richer in carbon until its composition reaches 4·3 per cent. of carbon. If the solution contains a little more than 4·3 per cent. of carbon, then graphite will separate out, reducing the composition of the residue to below 4·3 per cent. After this some iron will separate out, thus raising the percentage of carbon in the residual liquid, so that, on the whole, the composition remains constant. Thus it will be evident that iron containing 4·3 per cent. of carbon, whether originally prepared of this composition, or resulting naturally as an eutectic during the cooling, must solidify as a mixture of iron and graphite.

In the case of pure iron, let us suppose it to be in the fused state and then to cool down until it solidifies, which is considered to take place at about 1600° C. The solidified iron is then in a plastic state, to which the name of "gamma" iron has been given by Osmond. While it is in this form it is capable of dissolving about 0·9 per cent. of carbon at about 900° C. and rather more at higher temperatures. At 1000° C. for example it dissolves 1·5 per cent. of carbon. It must, however, be borne in mind that the solubility of a substance depends on the form in which it is presented to the solvent: thus carbon, in the form of graphite has a much lower degree of solubility at certain temperatures than carbon in the combined form, known as "cementite." This suggests a reason why steel contains more combined carbon than slowly cooled pig iron.

Now consider the case of solid carburised iron alone. When pure gamma iron cools to the point (*g*) in Fig. 87, which is at 890° C., it undergoes a change to another allotropic form, known as "beta" iron, and this change is attended by a considerable evolution of heat. This beta iron, like the gamma modification, is non-magnetic, but it

is less capable of holding carbon in solid solution than gamma iron. As the iron cools down to 770° C., as shown at point (*m*), another molecular change occurs and the beta iron changes to what is termed "alpha" iron, which is magnetic. Much heat is evolved, but less suddenly than at the previous change, probably because the iron is less mobile at the lower temperature. As beta iron dissolves but little carbon (probably less than 0·1 per cent.) the influence of carbon upon iron is practically eliminated at temperatures

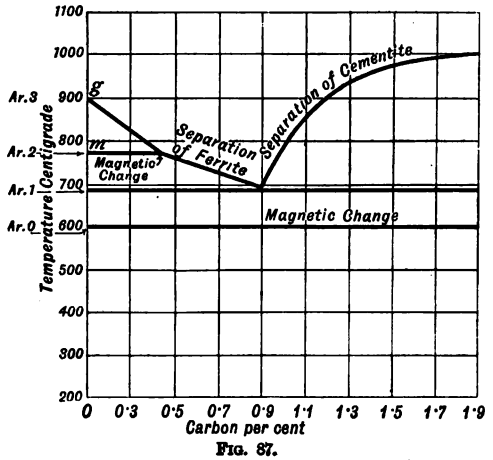


FIG. 87.

below the point of the change from gamma to beta iron. When the metal cools down to about 610°C another critical point is reached, marked *Ar.0* in Fig. 87. It appears to be the beginning of a slight molecular change which extends over a range of 100° and is accompanied by a change in magnetic properties.

It has been shown in Fig. 86 that in iron containing more than 1·2 per cent. of carbon there is a residual liquid which solidifies at a constant temperature of about 1130° C., and the microscope often shows the presence of graphite

in such an alloy, but with steels containing less than 2 per cent. of carbon the latter may be sometimes converted into carbide during the subsequent cooling. The iron, on the other hand, is always subject to changes during the cooling.

Now the eutectic line *aBc* (Fig. 86) has not been traced in steels containing less than 1·2 per cent. of carbon, hence we learn that at 1130° C. iron can hold 1·2 per cent. of carbon in solid solution. It might be inferred from this that at the higher temperatures at which the iron originally solidified it would contain more carbon in solid solution. There are, however, certain considerations which do not favour this view. One of these considerations arises from the fact that at rather lower temperatures, such as 1000° C., iron can hold more than 1·2 per cent. of carbon in solid solution, so that there is clearly some influence at work which causes, as the temperature rises, a decrease in the amount of dissolved carbon.

Now at 1130° C. an excess of carbon in iron would tend to separate as graphite, but at 1000° it would separate as carbide of iron, Fe_3C, and this is probably the main cause of the irregularity. This is borne out by the fact that pure carbide of iron, Fe_3C, when heated to about 1050° C., is dissociated, forming graphite, and iron containing some dissolved carbon. At temperatures then between 1000° and 1130° C., the dissolved cementite, being dissociated, tends to the liberation of "temper-carbon," either directly, or after an intermediary stage of simple solution in iron.[1]

Allotropic Theory.—Osmond has shown that there are three critical points, or evolutions of heat, on cooling a piece of very mild steel from a temperature of 1000° C.

I. A slight evolution of heat at about 890° C., termed Ar_3.

II. A disengagement of heat at about 765° C., termed Ar_2.

[1] Stansfield: *Iron and Steel Inst.*, No. 2, 1889.

III. Another point at about 690°, small in very mild steel and highly accentuated in steels high in carbon, termed Ar_1.

In pure iron, on cooling from 1000° C., when the iron is in a state which has been termed "gamma" iron, an evolution of heat is observed at 895° (the point Ar_3) when the iron is said to change from the gamma modification to the "beta" form. Another change occurs in very mild steel at 765°, after which the iron is said to be in the "alpha" form. The presence of dissolved cementite lowers the temperature at which these changes occur, in precisely the same manner as the presence of dissolved carbon in cast iron lowers the temperature of its freezing point.

Now take steel containing less than 0·3 per cent. of carbon, in which the points Ar_3 and Ar_2 both occur. Formation of beta iron from gamma iron occurs at points differing with the content of carbon. Iron in the gamma form will dissolve about 1 per cent. of carbon as cementite, at about 890° C., but beta iron will scarcely dissolve any carbon, so that the beta iron, being practically free from combined carbon, undergoes the change to alpha iron at the normal temperature of 765°. Meanwhile as the iron falls out, the residual solution becomes richer in cementite, until at 690° it is saturated, forming an eutectic solid solution, and the cementite and iron (in the alpha form) separate out, side by side, to form the well-known "pearlite." The evolution of heat at 690° marks the point known as Ar_1.

If the steel contains 0·34 per cent. of carbon the point Ar_3 occurs at the same temperature as Ar_2, and further additions of carbon result in the lowering of the temperature of the combined point $Ar_{2\text{-}3}$. In such steels the excess of iron separates out in the alpha form, and the residual solid solution is decomposed as before at the point Ar_1 at 690° C.

Gamma iron may be described as an allotropic non-magnetic condition of iron existing at temperatures above 895° C. It is said to crystallise in the cubic system, and that its crystalline forms are combinations of the cube and octahedron.

Beta iron is an allotropic non-magnetic condition of pure iron existing at temperatures between 765° and 895° C. It is isomorphous with alpha iron, and is said to crystallise in the cubic system.

Alpha iron is the normal condition of pure iron below 765° C. It crystallises in the cubic system. It is also magnetic. Therefore the appearance or disappearance of magnetism was formerly supposed to coincide with the point Ar_2, which, as already explained, is the change point from beta to alpha iron, or *vice versa*. In opposition to this view Roberts-Austen and Tomlinson have found that the point Ar_3 is intimately connected with the magnetic changes in iron, and the point Ar_2 is of secondary importance.

Allotropy is the capacity of an element to exhibit different properties, although its conditions are identical as regards chemical composition, physical state, and external influences (pressure, temperature, etc.). Roberts-Austen describes it as a change of internal energy occurring in an element at a critical temperature, unaccompanied by a change of state.

Howe prefers the following definition: Allotropy is a change in the properties of an element without change of state. It is habitually accompanied by a change of internal energy. It is due in some, and perhaps in all cases, to a change in the number or in the arrangement of the atoms in the molecule.

H. Le Chatelier[1] is of opinion that the method of

[1] *Jour. of Iron and Steel Inst.*, No. 1, 1894.

observing arrests on cooling or on heating is insufficient to elucidate the question of the allotropic transformation of iron. It can only serve for a preliminary qualitative study of the general phenomena which occur. He considers that the results obtained by the pyrometric method depend on two entirely distinct kinds of phenomena:

I. The molecular transformations intended to be studied.

II. The delays in those transformations analogous to those shown in nearly all chemical changes, such as supersaturation, surfusion, slow combustion, etc.

It is known that the rapidities of chemical reactions, and consequently of the delays in the completion of those reactions, are influenced by so large a number of conditions that it has hitherto been impossible to assign to them any precise law. There is therefore very considerable interest attached to the study of the changes in iron, and it is necessary to characterise the different states of iron by certain of their properties which may be measured at a constant temperature, and which enables time to be given for the completion of the transformations. The three most suitable properties appear to be: the linear dimensions; the electrical resistance; the magnetic properties.

The mechanical properties (strength, elongation, etc.) are not suitable, because they are to a considerable extent dependent on the structure, which are quite different kinds of phenomena from the molecular changes.

Now the changes in length are very slight, and therefore difficult to measure. Moreover, a bar of metal that has been heated, never, after cooling, resumes exactly its original dimensions. The electrical resistances are considerably influenced by the presence of impurities in consequence of the granular or crystalline structure of metals. The magnetic properties give rise to phenomena which are very complex, and difficult to interpret, on account of the

variations in the results, according to the intensity of the magnetic field employed.

The several changing points of iron appear to remain invariable in the presence of non-metal impurities, such as carbon, sulphur, silicon, etc. That follows from investigations concerning electrical conductivity. On the contrary, however, the delays in the change may vary considerably, owing to the presence of foreign bodies, as shown by the results of heating and cooling.

On the other hand these points of change are displaced, as proved by the study of electrical resistances, when isomorphic metals, such as nickel and manganese are added to iron. The points proper to each of these two metals are replaced by an intermediate point, the temperature of which depends on the proportion of the mixture. The main difference between the action of such metals and that of the more active non-metals is that while the metals mingle in a uniform manner with the iron to form the substance of the grain or crystal, the non-metals form chemical compounds and place themselves in the spaces between the crystals.

Prof. Arnold stoutly opposes the allotropic theory of iron, and maintains that there is no evidence of the presence of alpha-beta modifications of iron. Concerning the point Ar_1, he contends that its intensity is proportional to the amount of Fe_3C present in a series of ascending carbon steels and to the area of Sorby's laminae in the micro-sections. He further points out that the point Ar_2 marks the exceedingly faint evolution or absorption of heat, due respectively to the passage of the iron from a plastic to a crystalline condition, or *vice versâ*.

The critical point, concerning which the greatest difference of opinion exists, is undoubtedly the point Ar_3. Now, on heating a very mild steel to a full white heat in

vacuo for 17 hours, it was found that it was still evolving hydrogen. On cooling this steel, the intensity of the point Ar_3 was increased, and the point Ar_1 had disappeared. Osmond has quoted the result of this experiment as strong evidence of the accuracy of his theory that Ar_3 marks the gamma-beta change. Unlike Osmond, Arnold claims that the removal of a small percentage of gas could not so influence a physical change in iron, but attributes it to some internal chemical cause connected with the prolonged heating at so high a temperature.

He further justifies his position by taking a bar of mild steel containing 0·16 per cent. of carbon, and by a prolonged heating at a temperature below 1000° C., the curves showing evolution of heat at Ar_2 and Ar_3 remained stationary, but the point Ar_1 had nearly disappeared. In other words, the evolution of heat normally occurring at Ar_1 had, by long-continued heating of the bar, been raised 200°, and augmented the heat evolved at Ar_3. He explains these facts by the hypothesis, that the point Ar_3 marks the formation of a sub-carbide of iron, whilst the point Ar_1 is due to the combination of the elements to form the normal carbide Fe_3C, and that in low carbon steels a prolonged exposure to a white heat converts the normal into the sub-carbide. Now, with regard to these objections of Arnold, it must be admitted that in steels of a certain carbon content there are three distinct critical points: Ar_3, Ar_2, and Ar_1. With respect to Ar_1 there are no difficulties; it is simply a question of the formation of an eutectic solid solution, where the cementite and the iron (in the alpha form) separate out side by side to form the well-known pearlite.

The point Ar_2 is largely connected with the appearance of magnetic properties in a cooling bar of iron, which indicates that the change is rather physical than chemical,

and, as Arnold himself maintains, that this point marks the passage of iron from the crystalline to the plastic state, the change may be fairly claimed to be allotropic.

The point Ar_3 has been conclusively proved to be present in pure iron, hence carbon can have nothing to do with it. Osmond points out that the point Ar_3 coincides with:

I. A variation in volume.

II. The angular point in the curve in which electrical resistance and temperature are co-ordinates.

III. Another angular point in the curve which represents the thermo-electric property of iron.

IV. A perturbation in the feeble magnetic power of iron which continues above Ar_2.

With this group of phenomena, studied by the same pyrometer, the carbon change Ar_1 has no influence. Now, if these manifestations do not indicate allotropic transformation of iron, it is difficult to give any other reasonable explanation. In fact, one is led irresistably to the acceptance of the allotropic theory; at any rate, until some better one is advanced, capable of more perfectly explaining the above recorded changes. The great difficulty is to devise means of retaining the different allotropic forms down to the ordinary temperature. Of course, every allotropic form is naturally unstable beyond the limits of temperature, within which it is spontaneously produced, and only becomes stable by the intervention of external forces.

Now, in the case of iron, foreign matter profoundly modifies its properties, and among the elements which are usually present, carbon takes the first place. It has been abundantly proved that carbon has the greatest effect in lowering the critical points during cooling, and renders the gamma and beta varieties of iron stable within a range of temperature in which they are not naturally so. The

metals manganese and nickel come next to carbon in this respect, and indicate that this range may be extended below the ordinary temperature, because certain alloys of these metals with iron are not magnetic, and therefore retain gamma or beta iron at the ordinary temperature.

If then foreign elements tend to maintain cooled iron in one or other of its allotropic forms, the question arises, is the influence of an added element on iron in accordance with the periodic law? Osmond answers this question in the affirmative. Now, the atomic volume of an element is its atomic weight divided by its specific gravity, and the contention is, that the smaller the atomic volume of the added element the greater its power of hardening iron, or in other words, of retaining the cold metal in the condition of beta or hard iron.

Osmond and Roberts-Austen have divided the elements into two groups: I. Elements, the atomic volumes of which are smaller than that of iron. II. Elements, having atomic volumes greater than that of iron, and which tend to produce a more or less complete change of the iron in cooling into the alpha or soft form. This is shown in the table on following page.

It must be, however, borne in mind that the above speculation is only claimed by the authors to be a limited law. It assumes that the foreign body preserves in solution its natural and individual state, and does not form chemical compounds with the solvent. The starting point at which these compounds intervene is very variable. It is evident, therefore, that if this idea of atomic volumes is a law, it can only operate when the foreign element is present in very small quantity, and it is not sufficient to know the proportion of a foreign element present in steel, and the atomic volume of that element, to immediately foretell the exact properties the alloy will possess. Other things have

to be taken into consideration, such as the structure of joints, and crystallisation. In fact the mechanical properties of a metal are a complex resultant of the molecular structure, of the structure that can be rendered visible by the microscope, and of residual tensions. The volume of the atom of the added element only influences the first of these factors (the molecular structure), and must doubtless often be masked by others.

Column I. Hardening or beta iron producing elements.		Column II. Softening or alpha iron producing elements.	
Name.	Atomic Volume.	Name.	Atomic Volume.
Carbon, - -	3·6	Chromium, -	7·7
Boron, - -	4·1	Tungsten, - -	9·6
Nickel, - -	6·7	Aluminium, -	10·5
Manganese, -	6·9	Silicon, - -	11·2
Copper, - -	7·1	Arsenic, - -	13·2
Iron, - - -	7·2	Phosphorus, -	13·5
		Sulphur, - -	15·7

Phase Rule.—The phase rule as applied to steel has been made the subject of an article by Prof. Bakhuis-Roozeboom. A phase is defined as a mass chemically or physically homogeneous, or a mass of uniform concentration. The state of a phase is completely determined if the pressure and temperature, together with the chemical potential of its components are known. The phase rule is a rule for finding the number of phases that can exist in a system containing a certain number of components, having a certain number of degrees of freedom, and possible phases in equilibrium. In physical chemistry the term phase is understood to mean homogeneous particles that occur within a body, and are separated by dividing surfaces from the other parts of that body. Examples of phases occur-

ring in steel are—ferrite, martensite, and cementite; while pearlite contains two or three phases—ferrite, cementite, and sorbite. In applying the rule to iron and steel we have a system of two components—iron and carbon, and by phases of this system we understand all the distinct forms that may appear in the system. We may, therefore, consider the following phases—carbon; iron in its three phases of gamma, beta, and alpha iron; liquid solution; solid solution of carbon in gamma iron, or martensite; and cementite, Fe_3C. A phase may be liquid or solid, may be an element or compound, or a homogeneous mixture of variable concentration.[1]

With regard to solid carburised iron at temperatures above all known allotropic changes, we may have iron, graphite, cementite, and solid solution of carbon. The absence of graphite in most steels, even when annealed, arises from the fact that a solution of carbon in iron does not readily deposit graphite, even when it is considerably supersaturated with carbon, but that cementite will readily separate as soon as its separation point is reached. If we take the analogous case of a salt solution, we have three phases, namely, salt, ice, and solution, which can exist together at a certain temperature. In a similar way Roozeboom assumes that graphite, cementite, and solution can also exist together at a certain temperature. It must be remembered, however, that the solubility of graphite is less than that of cementite, and in the absence of mechanical pressure, it is difficult to conceive graphite, cementite, and solid solution of carbon in iron to be in equilibrium.

Saniter heated pieces of thin pure iron wire, embedded in charcoal for varying periods, at a temperature of 900° C., and found after 7 hours that 1·64 per cent. of carbon had been absorbed; and after 14 hours this was increased to 2·8

[1] *Jour. Iron and Steel Inst.*, No. 2, 1900.

per cent. Microscopic examination revealed the fact that pearlite with bands of cementite extended in all directions to the surface. After 21 hours' heating the total carbon was 2·95 per cent., and consisted of pearlite, cementite, and graphite. The cementite was segregated towards the centre, none of the bands extending to the exterior. The surface was coated with graphite. Jüptner concludes from the above that graphite is not the most stable form of carbon, and that

Mixed crystals + graphite = martensite + cementite.

He assumes that the absorption of carbon by iron at about 1000° C. is accompanied by the formation of martensite. In such cases where the martensite does not come in immediate contact with the carbon, as in the interior of the mass of iron, the separation of cementite occurs. We may conceive of the continuation of the carburisation until the carbon is wholly in the form of graphite and cementite, but with an increase of temperature the cementite is dissociated until we get martensite and graphite, and then graphite is more stable than the carbide.

CHAPTER XVI.

CARBON AND IRON.

IRON is capable of combining with carbon in all proportions up to 4·3 per cent., which amount appears to completely saturate it when liquid. If, however, elements other than carbon are present they may increase or lower the saturation point. Manganese, and especially chromium, have the property of greatly increasing the solvent power of the alloy for carbon, while on the other hand silicon and aluminium act in the contrary direction. Sulphur is considered to diminish the saturation point for carbon when the iron is in the liquid state, but to increase the quantity of chemically combined carbon during cooling, in both ways opposing the separation of carbon in the form of graphite.

The well-known process of cementation affords an excellent illustration of the remarkable power of carbon to diffuse into solid iron, and Colson has shown that when iron is heated in contact with carbon there is a mutual interpenetration of carbon and iron, even when the temperature is as low as 250° C. It may be presumed that occluded gases may be the necessary cause in the carburisation, but Roberts-Austen has proved that pure electrolytic iron can be carburised in vacuo by the diamond at a temperature far

below the melting point of iron, and under conditions which absolutely preclude the presence or influence of occluded gas. A steel rail containing 0·26 per cent. of carbon was submitted to further carburisation by the Harvey process during a period of 120 hours, and the curve obtained was found to be a true diffusion curve. On the other hand, when the process is reversed, and the carbon taken out of steel by an oxidising agent a similar curve is obtained, but in the reverse direction. Abel has shown that carbon can pass from a highly carburised iron into one of iron free from carbon, against which it is tightly pressed.

Bell raised the percentage of carbon contained in wrought iron from 0·04 to 0·4 per cent. by heating it in contact with cast iron.

Arnold[1] considers that the diffusion of carbon in the process of cementation presents two distinct varieties of "interpenetration."

I. The interpenetration of the substance corresponding to the formula $Fe_{24}C$ and pure iron, and the interpenetration of the normal carbide Fe_3C and the sub-carbide $Fe_{24}C$.

II. That the interpenetration of the sub-carbide and iron is more rapid, and takes place at a lower temperature than the interpenetration of the $Fe_{24}C$ and Fe_3C.

III. That the interpenetration of $Fe_{24}C$ and iron begins at Ar_2 (about 765° C.) and is coincident with the evolution in vacuo of gases from the iron. That the interpenetration of $Fe_{24}C$ and Fe_3C does not take place till a temperature of about 950° C. has been reached.

The above considerations would seem to indicate that it would be possible to convert iron up to the saturation point (0·89 per cent. carbon) at a temperature of about 800° C., but that it is not possible to produce supersaturated high

[1] *Jour. Iron and Steel Inst.*, No. 2, 1898.

carbon bars unless the temperature of the containing vessel be kept at about 950° C., which is the case in practice.

Roberts-Austen dissented from the view that carbon penetrates iron both in the form of $Fe_{24}C$ and as Fe_3C. Take the analogous case of the diffusion of salt in water. The former diffuses into the water until, for a definite temperature, saturation is effected. In the same way, at a definite temperature, carbon diffuses into iron until the saturation point for that temperature is reached. If it is desired to get an increased diffusion, the temperature must be raised, and therefore it is preferable to explain diffusion on purely physical grounds, rather than to introduce the inadmissible question of chemical formula. The fact that at a definite temperature, iron is saturated by 0·89 per cent. of carbon, does not afford the slightest evidence of the existence of the supposed compound $Fe_{24}C$.

Carbon may exist in iron as graphite, when it is mechanically mixed, or in chemical combination with the iron, or in chemical combination with a third element contained in the iron, or in solution. Carbon exists in iron in at least two distinct forms of combination. Abel found, by dissolving different steels in a chromic acid solution, whether after hardening, tempering or annealing, different quantities of a heavy grey-black carbide of iron, as an insoluble residue, attracted by a magnet, of nearly constant composition, and having the formula Fe_3C. The proportion of carbon as carbide was found to vary from about 5 per cent. in hardened steels to 93 per cent. in certain annealed steels, and the quantity in tempered steel was found to be intermediate between that of hardened and annealed steels. This carbide is soluble in boiling hydrochloric acid. It contains 6·57 per cent. of carbon. The other form of combined carbon is that variety that exists in hardened steel and which has been provisionally termed "hardening carbon." This latter

variety is more soluble in dilute acids than Fe_3C, which is practically insoluble in cold dilute acids.[1]

When steel is dissolved in nitric acid a brown solution is obtained, the intensity of the colour being proportional to the amount of combined carbon present. Jüptner considers that with regard to the colouring power of the various forms of carbon, this may be placed in the following order:

Carbide carbon,	100
Total carbon,	92·7
Pearlite carbon,	80
Martensite carbon,	52

They are therefore approximate in the following ratios:

Martensite carbon,	2
Pearlite carbon,	3
Carbide carbon,	4

Prof. Campbell[2] has studied the carbides of iron in steel by dissolving the steel in hydrochloric acid and passing the gas evolved through bromine, in order to convert unsaturated hydro-carbons of the general formula C_nH_{2n} into their di-brom derivatives $C_nH_{2n}Br_2$, the latter being then analysed and fractionally distilled for the purpose of quantitatively identifying the various constituents. From the percentage of bromine in the derivatives the average number of carbon atoms in the molecule were calculated.

The following conclusions were arrived at: (1) That in annealed steel the average number of carbon atoms in the molecule decreases as the percentage of carbon increases; (2) that the effect of hardening seems to be to lower the number of carbon atoms in the molecule of derivatives, and to increase the proportion of carbon escaping as gaseous paraffins; (3) from the percentage of carbon in the steels examined, the annealed samples, under 0·89 per cent. of

[1] Howe's *Steel*, p. 6. [2] *Jour. Iron and Steel Inst.*, No. 2, 1899.

total carbon, must consist of pearlite with ferrite, while those above 1 per cent. consist of pearlite, with quantities of cementite, increasing with the carbon.

The results obtained appear to indicate that there are several different carbides existing in steels, and that these carbides have different molecular weights. According to this view, the formula Fe_3C is merely an empirical one. The hypothesis offered by Campbell makes the fundamental assumption that carbon forms with iron a series of compounds that might be termed "ferro-carbons" on account of their similarity to hydro-carbons. This series of ferro-carbons has the empirical formula C_nFe_{3n}. In annealed steels containing less than 0·89 per cent. of carbon we should find the eutectic pearlite to consist of alternate laminae of C_nFe_{3n} and ferrite Fe_{21n}. The latter may be regarded as iron of crystallisation, the ferro-carbons occurring in pearlite having a higher molecular weight than those occurring as free cementite. When steel is heated above a certain temperature the ferro-carbons dissolve in the iron of crystallisation forming martensite, which may be represented by the formula $C_nFe_{3n}+Fe_{21n}$, or, according to Arnold, $Fe_{24}C$. When the ferro-carbons of high molecular weight dissolve in their iron of crystallisation, they probably begin to split up, yielding lower members of the series, this dissociation increasing with rise of temperature.

Against this iron of pearlite being iron of crystallisation, it must be remembered that there is no proof that pearlite is a chemical compound, but that the iron is similar to the ice crystals in a solidified cryo-hydrate, the two structural elements being merely in juxtaposition, and forming a mechanical mixture. There can, however, be little doubt that molecular alterations of carbon and iron take place at certain temperatures in heating and cooling steel, and that

polemerised iron carbides are capable of existing under certain conditions, so that iron carbides play a much more prominent part in influencing the properties of solid steel than elemental carbon. It is quite possible that carbon does exist in molten iron in a state of simple solution, and that the molecules of such carbon contain not more than two atoms, and in all probability are monatomic; but on solidifying and cooling, carbides are formed which cannot remain in solution at certain high temperatures unless the steel be suddenly quenched. On slow cooling the carbide falls out of solution as cementite. Now, if in high carbon steel, on cooling from a high temperature, an iron carbide solidifies, it must be before the eutectic solidifies, and this carbide is probably austenite, which at a lower temperature passes into martensite.

Tempering and Annealing.—The effect of temperature on the condition of carbon is well illustrated by reference

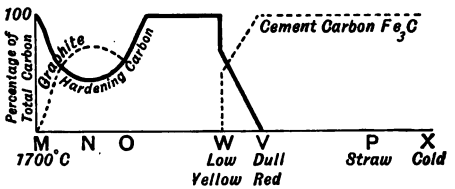


FIG. 88.

to Fig. 88 by Howe,[1] which shows the supposed influence of temperature on the relative strength of the tendencies to form graphite, hardening, and cement carbon. The graphite forming tendencies are at a maximum at N, which is at a white heat. The tendency to form cement carbon is at a temperature of dull redness; and the tendencies to form hardening carbon seem to reach two corresponding distinct maxima, one at above a white heat, and the

[1] Howe's *Steel*, p. 10.

other at a low yellow heat, the W of Brinnell. Now, in melted iron, the carbon must be present in solution or in combination, or partly in each condition. Were any of it present as graphite it would rise to the surface in virtue of its specific gravity, and would be found there on solidification. But such is not the case, for in the solid metal it is uniformly distributed through the iron, showing that it has been formed after solidification. The tendency to form graphite is confined to the range of temperature represented between the points M and O, and, if steel be kept for a long period at the temperature N, it becomes coarse-grained, due to the crystallisation, both of graphite and of the iron. Now, the crystalline structure of steel is generally unfavourable from the point of view of its industrial use, but this structure may be broken up by the mechanical work of forging the steel while hot; but, if the forging be continued below the point V, the iron is then in a different state and will possess different properties.

In annealed steel, practically all the carbon is in the cement state unless the annealing temperature has been too high, so as to approach the temperature represented by the point N. Moreover, at the point W, and up to the point O, the cement carbon is in solution in the iron, and, if suddenly cooled, will remain in what has been conveniently termed the hardening carbon state. On the other hand, if the steel has been gradually cooled to below the point V, the hardening carbon will be changed to cement carbon. At a temperature between W and V, iron undergoes a sudden expansion, and its thermo-electric behaviour is abnormal. Also a change in its magnetic properties is observed.

By reheating hardened steel to a certain point P, a straw colour appears on the brightened surface, which passes to a deep straw, a purple, a blue, and finally a black

as the temperature is gradually raised, all the above temperatures being below the point V, at which it is assumed that the carbon passes into the cement form on slow cooling, or into the hardening or solution form on heating up. Now the question arises, does the hardening carbon, in hardened steel, pass partially into the cement form during this tempering process? Howe considers that, while the tendency exists, it is held in check by what may be termed chemical inertia or viscosity. That as the temperature rises to a straw heat this viscosity is released and some of the carbon passes into the cement state, and the steel is therefore softened. At a blue heat still more of this change occurs. This harmonises with the fact that while hardened steel is softened by reheating, annealed steel is not hardened by being quenched below V. Hence below this point the cement state is permanent.

Wahlberg[1] states that the elastic limit is raised by means of heating up to 350° C., at the following rates:

In group I.,	with average carbon,	0·84	by 28	per cent.
„ II.,	„	„	0·39	by 24	„
„ III.,	„	„	0·20	by 20	„

With regard to ductility, the rates of increase are respectively 9, 6, and 12 per cent. The values obtained for ultimate stress show that the absolute strength is not much altered by this treatment. This shows that the heating up to 350° C. considerably increases the elasticity and tenacity, without materially affecting its absolute strength. The generally accepted notion is that any wrought material is rendered tougher by means of annealing and subsequent slow cooling, while at the same time the strength and elastic properties are reduced. From a general point of view this is true, and quite consistent with the structural

[1] *Jour. Iron and Steel Inst.*, No. 2, 1901.

changes occasioned by mechanical treatment. It is a common saying, that what is gained in tenacity is lost in elasticity, and that it is only in the case of unwrought material, such as ingots and castings, that a general improvement of all the physical properties takes place in consequence of annealing and cooling, whether slow or sudden. This is not the case, as a final annealing will improve any hot rolled metal.

Prof. Heyn has made a close study of the annealing of mild steel, and in a communication to the Iron and Steel Institute, September, 1902, he gives the following summary:

1. When low carbon mild steel is annealed at 1000° C., there occurs an increase in the degree of brittleness if the annealing period is sufficiently long. The increase is more considerable, and manifests itself the sooner the higher the temperature of annealing, and by a judicious adjustment of the annealing temperature and period, it is possible to produce any desired degree of variation in the brittleness of mild steel within definite limits.

2. Prolonged annealing, say uninterrupted for fourteen days, at temperatures between 700° and 890°, produces no increase in the brittleness. In such cases where the brittleness of the metal in its initial state is not yet at the lowest degree possible, by this treatment the lowest degree of brittleness will be attained.

3. Between 1100° and 900° there exists a temperature limit, above which, if annealing is carried on for a longer period and at an increasing temperature, the degree of brittleness increases. Below these limits, however, this is not the case.

4. Overheating not only occurs at a most extreme white heat, but manifests itself already at considerably lower temperatures, which must, however, exceed the tem-

perature limit referred to in No. 3, the degree being more marked the longer the annealing period.

5. By suitable annealing, the brittleness of overheated mild steel can be eliminated. If annealing is carried on above 900° C., the short period of about half an hour is sufficient. Longer annealing must be the more carefully avoided, the more the temperature limit referred to in No. 3 is exceeded, otherwise the signs of overheating reappear. Below 800° an annealing of even five hours is not sufficient to eliminate the brittleness in overheated mild steel, but by annealing for several days' duration, at temperatures between 700° and 850°, this object can be attained.

6. If mild steel, which has been annealed for a longer period, at a high enough temperature, so that after undisturbed cooling it would show extreme brittleness, is rolled or forged during cooling at a bright red heat, it will exhibit no brittleness when cold.

7. The fracture of overheated mild steel generally shows a coarse grain, although it is not necessarily always the case.

8. The single crystal grains of which the structure of the iron is built up, and which can be detected under the microscope by suitable etching, are often of considerable dimensions when in the state of overheating. Nevertheless, this is not to be considered as proof positive that overheating has taken place, since the period of cooling also exercises a great influence on the size of the ferrite grains. Rapid cooling, from the temperature causing overheating, produces fine ferrite grains, without appreciably reducing the brittleness. Moreover, it is possible by heating mild steel for days together, at between 700° and 890° C., to bring the material into such a condition that it will show exceedingly coarse ferrite grains, and yet not exhibit brittleness.

Heating for Tempering.—By cautiously reheating hardened steel to a certain point, the tension is greatly released,

some carbon or carbide is probably set free, the metal loses its brittleness, and becomes softer in proportion to the temperature to which it is raised; so that by this means various degrees of hardness may be produced in the same steel to suit the requirements of different articles. This operation is termed "tempering." The surface of the steel is made bright before heating, and when the temperature reaches 220° C. a faint yellow colour appears, succeeded by other colours as the temperature rises, so that the colour indicates the temperature of the steel, and therefore the degree of softness or "temper." These colours are due to a thin coating of oxide, which forms on the surface and produces the colour as an optical effect. The following table shows the tempers used for various articles, the lowest temperature indicating the hardest temper:

Percentage of Carbon.	Temperature.	Colour.	Article.
1·5	220° C.	Faint yellow.	Surgical knives.
1·3	230	Straw yellow.	Razors, knives, hammers, taps, and dies.
	255	Brownish yellow.	Scissors, hard chisels, shears.
	265	Purplish brown.	Axes, planes.
	277	Purple.	Table knives.
	280	Violet.	Cold chisels for brass, punches, etc.
0·9	288	Light blue.	Swords, coiled springs.
	293	Dark blue.	Fine saws, augers.
0·8	316	Blackish blue.	Hand saws, cold chisels for copper and wrought iron.
0·6	400	Black.	Spiral springs.

When the steel is heated much beyond the point 316° C., it becomes too soft for any kind of tools. The term "temper" is used to express the hardness, whether due to treatment or composition.

Springs may be tempered by dipping in oil and heating until the oil burns off with a white flame, when they are quenched in oil. Small tools are hardened and tempered in one operation. The red hot steel is quenched to a blue heat,

then rapidly rubbed bright and watched until the proper colour is observed, when they are plunged into cold water.

Tungsten and manganese steels are hardened by raising to a strong red heat and allowing to cool slowly. Chrome steel is quenched in water from dull redness.

Hardening.—When a piece of steel, containing about 0·3 per cent. or more of carbon is raised to a strong red heat and suddenly cooled by plunging into water or other liquid, so as to cool the steel rapidly, it becomes very much harder, and the process is termed hardening. The art of hardening steel is of great antiquity, for Homer describes it, and also shows that he was acquainted with the coloration tints that result on tempering. Pliny the younger describes the hardening of steel in his thirty-fourth book. He mentions various places where the waters were noted for their hardening effects. Not only did he know of water hardening, but he also observes that the finer class of tools were hardened in oil, to prevent them becoming as brittle as would result from hardening in water. The ancient smiths laid particular stress on the nature of the water used in the hardening process on the results obtained. The art of hardening weapons was in ancient times held to be a secret craft, and similar secrecy is maintained by many workmen and manufacturers at the present time.

The first to really study the hardening process was Reaumer, and although his views may appear to be crude, depending on the then existing theories as to the constitution of metals, they bear a close resemblance in some ways to those now held. After Reaumer came Rinman and a number of others. Since their time the subject has claimed considerable attention, and to-day rival theories are as vigorously contested as ever.

The theory now most strongly supported is that known

as the allotropic theory, which is stoutly opposed by the advocates of the carbon theory.

The allotropic theory, as advanced by Osmond,[1] and powerfully supported by Roberts-Austen is the result of investigations on the cooling of iron and steel with the aid of the thermo-couple introduced by Le Chatelier. See Fig. 3. Bearing in mind the fact that molecular change is accompanied with evolution or absorption of heat, he studied the slow cooling of masses of iron and steel, and recorded his results by means of a chromograph attached to a couple, composed of platinum and platinum alloyed with 10 per cent. of rhodium, converting the indications of the galvanometer into temperatures by Tait's formulae.

If a bar of unhardened steel be heated to say 500° C. and allowed slowly to cool, no break in the uniformity of the cooling curve occurs; but if the steel be heated to 900°, or even 750°, there are stages when the cooling is arrested. This is due to some molecular change in the steel that produces heat. Like irregularities occur during gradual heating. These effects may be observed with great accuracy by the aid of the Le Chatelier pyrometer. Thus in Fig. 89 the curves for pure iron, mild steel, and hard steel respectively, are obtained by observing the spot of light reflected from the mirror of the galvanometer, when the thermo-couple is attached to the cooling metal. Suppose the metal to cool uniformly at the rate of 2·2° per second, then at 858° there is a retardation of the spot of light, and what originally took 6·6 seconds here takes 26 seconds in the case of pure iron, and a similar retardation of 76 seconds in the case of hard steel. With respect to mild steel there are two breaks in the continuity of cooling, one above and one below 750° C. Now Osmond observed that the effects of cold working and quenching from a high tem-

[1] *Introd. to Metallurgy*, Roberts-Austen, p. 154.

perature were somewhat similar, and concluded that they must arise from a common cause. He supposes that the condition of the carbon is probably not changed by cold working, and therefore the hardening effect is due to an allotropic change in the iron itself. He considers that iron assumes two or more allotropic states, namely: (α) iron which exists in soft iron and steel, and is itself soft and malleable; (β) iron which is hard, strong, non-magnetic, and brittle, and which exists in hardened steel; (γ) iron

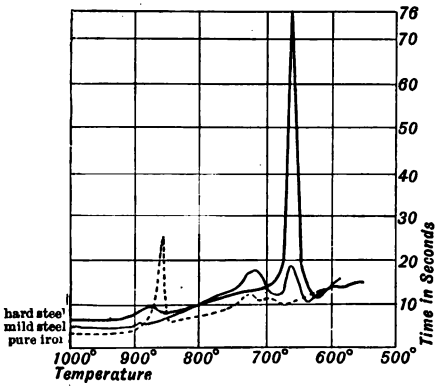


FIG. 89.

which is also non-magnetic and exists at temperatures above 860°C. He states that one variety changes to the other variety at certain critical temperatures. If carbon and other bodies are absent, these changes occur rapidly, and however quickly pure iron is quenched from a high temperature, the gamma iron is changed to the beta and alpha forms in succession. But if carbon is present it impedes this passage from one kind to the other, and if the steel is suddenly cooled the iron remains in the beta form, and is therefore hard. That in cold working the alpha is also changed to the form termed delta. In the curve (Fig. 89)

it will be observed that there are two irregularities in the cooling of mild steel: the first is assumed to be due to the beta-alpha change, and the second is due to the passage of hardening into cement carbon. This point was first observed by Gore, and afterwards by Barrett, who gave the name of recalescence to the phenomena of reheating exhibited by iron when cooled to a certain point. Osmond reasoned that if steel be quenched below the temperature represented by the first break, but above the temperature at which the carbon change occurs, then the steel should be soft and yet the carbon not in the cement form, and such he affirms to be the case. It follows from this that, although the presence of carbon is essential to the hardening of steel, the change in the mode of existence of the carbon is less important than was formerly supposed. The alpha modification of iron may be converted into the delta form by stress applied to the metal at temperatures below a dull red heat, provided the stress produces permanent deformation of the iron.

Osmond further found that the appearance of magnetism in iron coincides chiefly with the middle point in cooling steel. It has been further proved that there are two distinct critical points, named respectively Ar_2 and Ar_3, hence there must be three allotropic forms of iron; the one above Ar_3 is termed gamma iron.

Roberts-Austen[1] says "the most interesting information which the pyrometer has yet afforded is in connection with the measurement of internal stresses in iron and steel. It is evident that the occurrence of molecular changes must be of vital importance when the metal is subjected at high temperatures to mechanical operations, such as rolling and forging. The question naturally arises, do the molecular changes in the iron take place at one moment throughout the mass of metal? or does the external portion of a hot

[1] *Introd. to Metallurgy*, p. 158.

ingot cool so much more rapidly than the internal portion, as to allow the molecular changes in the iron, and the alterations in the relations between the carbon and the iron, to become complete near the surface long before they take place in the interior of the mass? The pyrometer gives important evidence on this matter. If a steel, containing 0·9 per cent. of carbon be allowed to cool under pressure it will be found that the point of recalescence is lowered."

The term "hardness" is often used to express somewhat distinct properties. There are two methods generally used for testing hardness, namely, by indentation with a pointed tool, and by scratching with a hard point, such as that of a diamond. By indentation, a certain amount of material is pushed aside. In such a case we are measuring to some extent tenacity and ductility and calling it hardness. By scratching, we are measuring hardness, as understood by the mineralogist, and this may be termed abrasion hardness. This is the sense in which the term hardness is used in speaking of the different degrees of hardness in hardened steel. In fact we often group under the single term hardness, several different composite properties, which may bear no closely fixed relation to each other, such as resistance to compression, to indentation, and to scratching. Cohesion plays a very important part in all of them, and the cohesion varies with the nature and application of any stress put upon a metal. Hence one of three metals may best resist compression, a second best resist indentation, and a third best resist scratching. These properties differ entirely from brittleness and such expressions as brittle-hardness had better be avoided.

Mr. H. M. Howe[1] in discussing the allotropic theory says "There are two prominent theories of hardening, and both hold that sudden cooling acts by retaining a special

[1] *Jour. of Iron and Steel Inst.*, No. 2, 1895.

condition which is reached at a red heat, but which would be departed from on slow cooling. On the carbon theory, it is a special known hardening condition of carbon: on the allotopic theory, it is a suspected hard, strong, brittle beta modification of the iron that causes hardening, and that the carbon simply acts in retarding the change from hard beta to soft alpha iron. With the allotropic theory is associated the belief that the distortion in cold working also induces the beta modification, or another modification that is called delta iron."

Howe considers that the effects produced by cold working in modifying various qualities of the metal are too great to be referred to mechanical action, hence they must be due to some physical or chemical cause. The chemical condition of carbon does not change, therefore the iron must change allotropically. One strong argument in favour of allotropy is the sudden disappearance of magnetic properties on heating; the sudden change of specific heat, and the spontaneous retardations that occur in cooling practically carbonless iron, which, when sufficiently rapidly cooled, also has its tenacity nearly tripled. The effects of cold working and sudden quenching are identical in raising the elastic limit, tenacity, hardness, and brittleness, and in lowering the density. But the difference between hardness, brittleness, and conductivity is enormous, and gives rise to the question as to whether delta and beta irons are identical. With respect to the action of carbon, Howe suggests that hardening is not due to beta iron alone, carbon acting only as a heater, but to a combination of beta iron with carbon. This is called the "carbo-allotropic" theory. From the non-magnetism of beta iron and of manganese steel, the latter is supposed to contain beta iron. The great tensile strength of quenched carbonless iron is also assumed to be due to beta iron, but in this case there is an absence of

glass-hardness and brittleness, therefore beta iron may be assumed to be a strong, ductile, and moderately hard substance, and beta-carbide exceedingly hard and brittle.

The carbo-allotropic theory may be formulated thus: Hardening is due to the preservation, by sudden cooling, of a hardening carbide of beta iron, of perhaps varying composition, and often, especially in low carbon steel, to beta iron alone, but the hardening carbide gives much the greater hardness and brittleness; and, secondarily, to intense residual stress.

With respect to practically carbonless iron, Howe has shown that the effect of quenching in frozen mercury is to increase the elastic limit 157 per cent., the tenacity 54 per cent., and the elongation 95 per cent. An electrolytic iron, containing 0·009 per cent. of carbon gained in strength, but not to the same extent as the above. It was also noted that the transverse strength and the elastic limit are benefited much more than the tensile strength. The hardness is also greatly increased. These results are altogether out of proportion to the amount of carbon present. As mechanical treatment produces somewhat similar results, they might be ascribed to the stresses applied, but quenched copper and other metals give negative results, therefore the effects can only be ascribed to allotropy.

Mr. R. A. Hadfield opposes the allotropic theory for the following reasons: "If beta iron is hard and non-magnetic, why is not hard carbon steel non-magnetic? As a matter of fact, it can be highly saturated with magnetism, and under certain conditions can be made to retain more magnetism than any other kind of steel. Now the allotropists say that it is owing to the presence of some alpha iron. Thus a magnet of glass hardened steel is hard because of the hard and non-magnetic beta iron, but is magnetic

because of the soft alpha iron present. If alpha iron exist in hardened steel, evidence of its presence must have been detected in the most minute researches made by chemists and microscopists. But neither physical, mechanical, nor chemical research has found such a form. In a bar of steel, of uniform hardness throughout, such tests ought to have discovered it if any alpha iron was present. Besides, the harder the steel was made by rapid quenching the more beta iron there should be present, and yet the highly hardened steel is the best suited for magnetic purposes. Again, it was not sufficiently recognised how extraordinarily sensitive to change was the hardening carbide of iron, termed by Arnold the sub-carbide $Fe_{24}C$. Those changes occur far below the points at which claims are made that they are due to the change in condition of the iron Arnold states that changes commence at as low a temperature as 100° C."

Le Chatelier [1] states that the term "negative hardening" is used in France to indicate the method by which steel is cooled down to the ordinary temperature from about 800° C., under conditions which, while they do not interfere with the alteration in the texture of the metal, yet do so as regards that degree of hardening which is marked by the presence of a large proportion of hardening carbon. If, for instance, soft steel at a temperature of 800° C., is plunged into boiling water, no hardening ensues, but the texture of the metal becomes fibrous, and the degree of brittleness is considerably reduced. In this way a sample of steel that has been heated too long, or at too high a temperature, can recover all its former properties. The process may be dangerous in case of objects with sides of such varying thickness that strains may result on this cooling treatment. In such cases the object should be heated to 800° or 900°,

[1] *Bull. de la Soc. d'Encouragement*, vol. x., pp. 1336.

then cooled rapidly to 600°, then allowed to cool slowly to the ordinary temperature. The sudden cooling to 600° produces no hardening, but it produces a change of texture. In the case of armour plates some are plunged into molten lead, and in others the doors are left open until the temperature has dropped to the necessary point. In others again the furnace has a moveable bottom, and this is subsequently run out with the heated materials upon it: the latter are then cooled down to 600° in air, when the bottom and its contents are then run back again and allowed to cool down slowly.

"Double hardening" consists of a preliminary hardening, followed by annealing at a lower or higher temperature, with a view to eliminate strains, and then again hardening. This double hardening does not affect the strength and extensibility of the metal, but it eliminates the yield-point, which is very important in the case of springs, etc. A spring, hardened in the ordinary way, is completely pressed together when the yield-point is reached, but with a double hardened spring this is different. As soon as the limit of elasticity is exceeded, it suffers a slight deformation, but the limit of elasticity immediately increases again, and the deformation ceases. Double hardening also decreases brittleness.

Le Chatelier has found that in the case of iron wires the result of repeatedly applied slight blows is greater than that resulting from one sudden and heavy blow, a much increased elongation resulting before fracture. When, however, the wire is submitted to the double hardening process, it is found to exhibit the same elongation with rapidly applied force as with a slowly applied force. The method is used at Le Creusot for guns and armour plates. At other works it is used for machinery made of steel of a medium degree of hardness.

With respect to the hardening of steel Ledebur[1] mentions the following case: If a bar of steel is hammered until it is cooled down below a red heat, and then by rapidly repeated hammer blows is again raised to a distinct glow, and is then allowed to cool down slowly, a considerable proportion of its carbon content is converted into temper carbon, which is generally visible to the naked eye as a black seam, and which remains undissolved when the steel is dissolved in nitric acid. The steel has become softer and does not harden, or does so only to a slight extent, although its texture, on plunging into water, changes in exactly the same way as it would do had hardening actually resulted, and the temper carbon can then no longer be detected on the fractured surface by the eye. It is possible that the same effect can be produced by long-continued heating, and it is also possible that mechanical treatment can of itself, under certain as yet unknown conditions, either directly bring about changes in the condition of the carbon, or at least favour such changes.

The changes of structure brought about by heat treatment in carbon steel are admirably summarised by Mr. Sauveur[2] as follows:

1. When a piece of steel, hardened or unhardened, is heated to a certain temperature (W),[3] all previous crystal-

[1] *Stahl und Eisen*, vol. xv., pp. 944.

[2] *Jour. Iron and Steel Inst.*, No. 2, 1899.

[3] In these propositions the letter V indicates the temperature at which hardening carbon is changed to cement carbon during the slow cooling of steel; a change that is accompanied by a retardation in the rate of cooling, indicating an evolution of heat, sometimes so considerable as to produce an actual rise of sensible temperature of the cooling metal. In other words, V represents the critical point known as recalescence. The temperature V varies with the carbon content, being lowest in the most carburised steels. The letter W indicates the temperature at which takes place the opposite phase of

lisation, however coarse or however distorted by cold work, is obliterated and replaced by the finest structure the metal is capable of assuming; the structure of burnt steel, which cannot be effaced by such treatment, being the only exception.

2. When a piece of steel, hardened or unhardened, after being heated to the temperature W, is allowed to cool slowly it retains the fine amorphous structure which it had acquired at that temperature. It possesses then the finest structure that unhardened steel is capable of assuming.

3. When steel, hardened or unhardened, after being heated to the temperature W, is suddenly cooled from that temperature, by quenching in cold water, for instance, it is fully hardened. The metal then possesses the finest structure that hardened steel is capable of assuming.

4. When steel, hardened or unhardened, is heated to a temperature above W, and allowed to cool slowly and undisturbedly, the metal, whose crystallisation has been obliterated by its passage through W, crystallises again, the crystals increasing in size until the temperature V is reached, below which there is no further growth.

The fact that all crystallisation previously existing in the metal is obliterated during the W change is generally admitted. Also that steel crystallises while cooling from above W. There is, however, a widespread opinion that the metal does not attain, until the cooling begins, the fine amorphous-like structure acquired at W, but on the contrary, begins to crystallise immediately the temperature W is passed, and continues to do so while its temperature is

the same phenomena, *i.e.* the passage of cement carbon into hardening carbon during the heating of steel, which transformation is accompanied by a retardation in the rate of heating, indicative of an absorption of heat. The temperature W is about 30° higher than V.

rising. Some on the other hand believe that steel does not crystallise while its temperature is rising.

The statement that steel crystallises while its temperature is rising is opposed to the very nature of crystallisation, and on that account should not be accepted without conclusive evidence. Steel, above the critical range has been likened to a solid solution. The crystallisation of a solution consists of the segregation of its structural components taking place at a certain temperature and in a certain order. The contention that steel does crystallise above W, while its temperature is rising, is based on the fact that when a piece of steel is quenched at a temperature above W, its structure will be the coarser the higher the temperature from which it is quenched, from which it is inferred, that its grains must have grown during the heating previous to quenching. It should be remembered that it takes an appreciable time for a piece of steel to cool down to V, and if the piece is large the time will be considerable, and may be such that the central portion is not hardened at all. Now, the larger the piece the larger will be its grains or crystals, which would indicate that the longer time of cooling facilitates the formation of larger crystals during cooling. Sauveur says, "If it should be shown beyond doubt that steel does crystallise on a rising of temperature, the phenomena could not properly be called crystallisation: granulation would probably be a more correct term."

Mr. Stead has shown that when a piece of iron or very mild steel is subjected to a prolonged heating between 600° and 750° C. (therefore below W), its structure becomes coarsely crystalline, but with steel containing 0·2 per cent. of carbon and upwards this is not the case. The effect is therefore confined to very low carbon steels, and only then on prolonged heating. Such metal is practically a mass of ferrite, and develops a coarse crystalline structure be-

tween the above-mentioned temperatures; but as the carbon increases the ferrite diminishes up to 0·9 per cent. of carbon, when it disappears.

Osmond and Howe strongly support the view that crystallisation of steel occurs during heating. If two pieces of steel, containing 0·45 per cent. of carbon, were heated to 1200° C., and one was quenched and the other cooled slowly, the martensite grains in the hardened piece would not be much smaller than the pearlite grains in the unhardened piece. Howe remarks that, solid solutions are not exactly assimilable to liquid solutions. For a crystal to grow, it must find free solid crystalline molecules within reach. In a liquid solution this condition only occurs usually during cooling, but in a solid solution it can prevail during heating.

Methods of Hardening.—It may be stated first that the hardening capacity of a given steel, beginning with 0·1 per cent., increases with the percentage of carbon until 0·5 per cent. is reached, when it becomes nearly constant with ascending rates of carbon until 0·9 per cent. is reached, beyond which there is a slight decrease. With regard to the value of various quenching liquids, the tables on the following page by Brinnell will indicate the effects.[1]

It will be observed from these tables that the same quenching liquid differs to a certain extent with regard to the degree of hardening, according to the amount of carbon in the steel hardened.

It is generally considered that, in the case of tool steels, the best general results are obtained by employing the lowest quenching temperature which suffices to give the required hardening, as needlessly high temperatures impart a coarse structure and consequent brittleness, which cannot be wholly effaced by subsequent treatment. In general the

[1] *Jour. Iron and Steel Inst.*, No. 1, p. 269, 1901.

HARDENING EFFECTIVENESS OF QUENCHING LIQUIDS

From a Temperature of 880° C. with 0·1 per cent. Carbon, and at 780° for the 0·45 per cent. and the 1·25 per cent. Carbon.

Material.	Hardness Number. Before Hardening.	Hardness Number. After Hardening.	Hardening Capacity.	Quenching Liquid.
High quality mild steel, with 0·1 per cent. carbon	99	112	1·13	Lead, 350° C.
	99	118	1·19	Boiling water
	99	121	1·22	Wood tar, 80°
	99	149	1·51	Water, 20°
	99	156	1·58	Salt solution, 20°
	99	202	2·04	Soda solution, 20°
Steel with 0·45 per cent. carbon	202	217	1·07	Boiling water
	202	235	1·16	Wood tar
	202	241	1·19	Lead
	202	627	3·10	Salt solution
	202	652	3·23	Soda solution
Steel with 1·25 per cent. carbon	311	387	1·24	Boiling water
	311	430	1·38	Wood tar or lead
	311	495	1·59	Common water
	311	627	2·02	Salt solution

more rapid the cooling the harder and more brittle is the steel; rapidity of cooling up to a certain point increases the tensile strength, but if the cooling be exceedingly rapid the tensile strength may be lowered, and the steel may even be broken by the hardening itself. The influence of hardening temperature on the hardness result is shown in the following table by Brinnell:

Steel.			Hardening Temp. 690° C.	Hardening Temp. 750° C.	Hardening Temp. 1000° C.
C.	Si.	Mn.	Hardness No.	Hardness No.	Hardness No.
0·1	0·01	0·1	134	163	137
0·7	0·30	0·5	235	460	430

The proper hardening heat is fairly well defined within certain limits, the lower limit being the temperature required in order to effect a transformation of cement into hardening carbon, below which there can be no hardening at all, except a certain hardness mechanically effected in consequence of the sudden cooling. The upper limit is the temperature which should not be exceeded, in order to avoid the formation of a more or less coarsely crystalline structure.

As manganese and silicon are invariably present in steel, and therefore must exert some influence on its hardening properties, it is well to know what is the exact relation between these elements as regards their power of producing hardness. According to Brinnell the ratios are as 5 : 3 : 1. That is to say, carbon hardens five times as much a manganese, and nearly twice as much as silicon.

The hardness and brittleness of hardened steel are influenced far more by the rapidity with which the steel cools down to 400° C. than by the rapidity of cooling below 400°, though the latter is not without its influence on the resulting hardness. Oil hardening is often resorted to where high tensile strength, together with high elongation, are required. This is the case with steels containing less than 0·75 per cent. of carbon, used for guns, marine shafts, armour plate, etc., because here tensile strength is more important than hardness, hence they are generally hardened in oil. For cutting tools hardness is more important than strength, hence they are hardened in water. For large pieces a running stream or spray of the quenching liquid is needed.

In dealing with large pieces as regards hardening, it will be evident that the exterior is cooled much more rapidly than the interior, and on considering a section taken from the centre to the outside, it may be looked upon as composed of a number of concentric layers, each under a different degree of tension, due to the unequal expansion,

and the outer layers, contracting the most, may be so strained as to split into parts, or at any rate be badly warped. To avoid such defects various devices are resorted to, such as fixing pieces of steel on to the outer portions. When, as in eccentrics, holes occur near the periphery, there is great liability to cracking, since the outer rim is then in the condition of a band shrunk on a cylinder, and nearly cut through at one point: the contraction of the band is here resisted by such a small area of cross-section that fracture is likely to occur. So too when a piece has sharp re-entering angles on the exterior it is liable to crack. In most cases it is advisable to well agitate the cooling liquid while the steel is being quenched. Long and narrow pieces should be immersed lengthwise, otherwise the metal will be warped. If the piece is immersed sideways the side first touching the water will contract and become concave for an instant; the upper side cooling and contracting after the lower side has become cold will not completely compensate for this initial curvature, and the piece will remain distorted.

Effect of Hardening on the Physical Properties.—The effect of hardening in producing strains in hardened steel has already been indicated; this is due to the unequal contraction of the interior and the exterior, and as the exterior becomes cool first, and therefore contracts, while the interior is hot and expanding with regard to the exterior layer, it thus prevents the steel as a mass from assuming its original dimensions: this internal stress may become so great in certain cases as to overcome the ultimate strength of the outer layers, and cause it to crack. The mass as a whole is permanently enlarged, and the specific gravity of the whole is less than it was in the unhardened state. Holley verified the fact of external compression and internal tension by slitting a hardened steel bar in two lengthwise, in a planing machine, when each half became curved, being concave on the

planed side. Barus and Strouhal also have experimented on this subject. On progressively removing layer after layer from the exterior of a hardened steel bar, they found the specific gravity of the residual core to increase with surprising regularity.

The increased tensile strength of a hardened steel bar is attributed by Howe to residual strength. He looks upon a hardened steel bar as consisting of a set of springs, the outer ones in compression and the inner ones in tension, owing to the residual stress, which is due to contraction at dissimilar rates. Extraneous tensile stress, applied by grasping the outer spring (as happens when such a bar is pulled apart in the testing machine), is not resisted by the outer springs until they have elongated by as much as they were originally compressed, the inner springs in the meantime supporting the whole extraneous stress, in addition to their initial residual stress. This condition, the opposite to that in an annealed bar, tends to favour the outer springs at the expense of the inner ones. Residual stress then, if moderate, should increase the tensile strength of the system by tending to equalise the stress borne by the several springs, through counteracting the effects of interstratal yielding; and when it becomes intense enough to exactly balance them the tensile strength should reach its maximum, again declining as with still more sudden cooling the still more powerful residual stress throws an excessive proportion of the stress on the inner springs.[1]

The same simile may be applied to the principle of ductility. The inner springs are under such initial tensile stress that they break simultaneously with the outer ones, and we get but little elongation, and, since the final area is not diminished by the drawing asunder of successive outer layers, but little reduction of area. The influence of carbon

[1] Howe's *Steel*, p. 29.

and that of iron in its different allotropic states has previously been alluded to as regards their probable influence in hardening of steel.

An ingenious theory of the cause of hardening of steel has been advanced by Akerman. Recognising that residual stress may lower tensile strength, he attributes the changes in hardness, ductility and structure, as well as the chief changes in tensile strength, caused by sudden cooling, to compression, which forces carbon into the hardening state, thereby increasing the hardness and strength, but diminishing the ductility, and breaking up the coarse structure.

Hardening of different Tools.—All kinds of steel expand on hardening, varying with the amount of carbon present. The temperature, to which steel should be raised for purposes of hardening, must be regulated according to the quantity of carbon it contains, since overheating is highly injurious. The harder the brand of steel, that is, the more highly carburised it is, the lower will be the temperature required; moreover a small article will require a lower temperature than a large one made of the same steel, because it is more suddenly cooled. Bulky articles, such as the face of an anvil, cannot be hardened by plunging into water face downwards, but must be placed upright in water and deluged with a large stream of cold water falling from above. The same remarks apply also to smaller articles having steel faces.

In hardening files it is important to protect the teeth from oxidation during heating; this was formerly done by covering them with a fusible paste, made of common salt and flour or ale-grounds. The files are heated in a coke fire, then placed on a block with lead rests and straightened with a leaden hammer. The workman, holding the tang by means of tongs, dips the file in a saturated solution of salt and water, and removes it when the hissing

noise ceases. If the file has warped, it may be sprung a little by means of pressure exerted by the workman. The hardening of edge tools is effected by heating in coke-fires and plunging them into water. They are then rubbed bright and tempered by placing on a thick cast-iron plate which is below a red heat Those tools, such as plane-irons, which are made of a combination of steel and iron invariably become convex on the steel side and require to be set by placing them iron side downwards on an anvil and hammering the steel side with a particular shaped hammer. The setting of cast steel chisels, knives, etc., is done by placing the convex side on the anvil and striking the other side with a setting hammer.

Saws are hardened by heating them in an air-furnace and dipping into whale-oil, or a mixture of whale-oil and tallow. Care is required in removing them from the furnace so as not to bend them with the tongs. They are next tempered by being passed over a clear charcoal-fire until the oily matter is burnt off. The saws are then flattened while warm, and any buckling removed by careful hammering. A method adopted by some hardeners of steel is to heat the article in a bath of molten lead kept at a uniform temperature, by which all parts are equally heated. This plan is said to be well adapted for all kinds of cutlery as well as files. In hardening irregular shaped masses of steel the more bulky part should be immersed in the water first, if possible, and the more pointed parts last. To prevent buckling in pieces of irregular shape and thickness, encasing the thinner parts in iron and hardening as a whole is sometimes resorted to. To harden hammer-heads, which are steel faced, the eye-part must be kept cool, with a wet rag, while the faces are heated.

Blue-short.—Iron and steel are more brittle at a blue heat than in the cold or at a red heat, and while mere exposure

to a blue heat does not permanently make the metals brittle, yet if they are worked at that temperature they remain brittle after cooling. The diminution in ductility is enormous, but it may be restored by annealing at 900° C. Iron and steel worked at a blue heat become crystalline. Steel that has been worked from a strong red to a blue heat also becomes brittle, and flow-lines may be observed in various directions from the part where the pressure was applied. These flow-lines often culminate in a crack.

Ridsdale[1] points out that normal mild steel, on which work has been continued to below the critical temperatures shows a uniform structure with small and ill-defined crystal grains, those at the edge being often smaller than those at the centre. If the steel has been heated too long, or at too high a temperature, yet not sufficient to burn it, the crystal grains will be larger at the outside than at the centre of the bar, due to the burning out of the carbon at the exterior. Microscopic examination shows that steel at a blue heat is in a condition of peculiar sensitiveness, so that it readily retains the effects of shock or work. This is probably due to there not being sufficient heat for the strained parts to readjust themselves whilst cooling, as is the case when work is finished at a red or white heat. It appears from the above that temperature is perhaps the most important factor in determining the brittleness or otherwise of steel. There is a temperature beyond which steel cannot be heated without being burnt, but there is also a temperature much below this which promotes brittleness. This temperature for mild steel is somewhere in the neighbourhood of 700° C., especially if the heating is very prolonged. The effect of continued annealing at this temperature is to considerably increase the size of the grain, which is generally an indication of weakness, but such brittle steel may be restored to its

[1] *Jour. Iron and Steel Inst.*, No. 2, 1899.

natural toughness by heating to 900° C. and allowing to cool slowly. These remarks only apply to normal steel of good quality, as with steel containing much phosphorus, say 0·2 per cent., re-annealing does not produce toughness although it changes its structure. Phosphorus tends to produce inter-granular weakness by the formation of a fusible phosphide.

Effect of Work.—Wrought iron is improved by fagoting and welding several times, as explained in connection with reheating and welding, and the same improvement is observed in working ingot metal. Up to a certain limit, and avoiding working at a blue heat, the tensile strength and elongation is increased by cold rolling or hammering, also the elastic limit is raised and the reduction of area is greater. The higher the carbon, up to a certain limit, the greater is the gain in tenacity, both in annealed and unannealed steel. If the sectional area of a piece of steel be reduced 30 to 40 per cent. by hot working, each per cent. of diminution of area increases the tensile strength and elastic limit by about 0·2 per cent., and the elongation and contraction of area by about 1·5 per cent.[1] Hot working may be beneficial by expelling slag, by welding detached particles, by closing blowholes and pipes, and by preventing crystallisation. The effect of hammering and rolling is not the same, for the former pushes, while the latter pulls the metal into the desired form. Howe considers that the superiority of hammered bars is due to the fact that the hammer finishes the bar at a much lower temperature than the rolls. In the case of weld metal, the sharp blow of the hammer may expel the slag more effectively than the more gradual squeeze of the rolls.

Welding Steel.—It is much more difficult to weld steel than iron, and the greater the amount of carbon the greater

[1] *Metallurgy of Steel*, Howe, p. 245.

is the difficulty. Various fluxes have been recommended to prevent the carbon burning away, and to render the welding surfaces clean, but few of them have come into common use; sand, and a mixture of borax and sal-ammoniac being the best. It is important that the temperature of the metal should not be raised higher than absolutely necessary; the higher the amount of carbon the lower should be the temperature used, hence the necessity of heavier hammers. The pieces should be tapped gently at first, and when they have begun to adhere they may be struck more heavily. The temperature at the finish must not be too low. It is best to work the steel rapidly, reheating as often as necessary (in order to prevent finishing too cold), and to anneal the whole piece when finished, so as to correct the effect of local hardening. When steel is to be welded to iron, the latter may be at a higher temperature than the former with advantage.

Carbon and sulphur lessen the welding power; the effect of silicon is not fully known; phosphorus in small amounts favours welding, but the joint is not so strong as when free from phosphorus. Oxide of iron, if not dissolved by the flux, is perhaps the most frequent cause of a bad weld.

Electric Welding.—The pieces to be joined are tightly pressed together, and the junction raised to the welding point by a powerful electric current of very low potential. The metal is heated by the resistance it offers to the passage of the current. The ends to be united are often made convex, and are forced together as the metal softens by the heat.

COMPOSITIONS OF VARIOUS STEELS.

	C.	Si.	Mn.	P.	S.
Shafts and boiler-plate,	0·16	0·03	0·30	0·04	0·03
Wire,	0·05 to 0·10	0·04	0·50	0·04	0·05
Gun barrels,	0·22	0·20	0·03	0·02	—
Structural steel,	0·25	0·06	0·50	0·03	0·01
Guns,	0·30	0·04	0·50	0·04	0·10
Axles and rails,	0·40	0·01	1·00	0·10	0·04
Rolls and springs,	0·50	0·20	0·40	0·04	0·05
Cutlery and American rails,	0·50 to 0·60	0·10	0·60 to 1·00	0·05	0·06
Projectiles,	0·60	0·25	0·60	—	—
Chipping chisels and tools,	0·75 to 0·85	0·02	0·40	0·05	0·06
Dies,	0·80	0·02	—	0·02	0·01
Setts,	0·85	0·13	0·40	0·03	0·02
Saws,	0·90	0·30	0·30	0·03	—
Drills and turning tools,	1·00	—	0·30	—	—
Hard saws, taps and dies,	1·10 to 1·30	0·02	—	0·04	0·03
Saw files, and 14″ files,	1·30	0·10	0·20	0·05	0·03
Razors and lancets,	1·50	0·10	0·20	0·05	0·03

CHAPTER XVII.

EFFECTS OF VARIOUS ELEMENTS ON STEEL.

Steel and Silicon.—Iron alloys with silicon in all ratios up to about 50 per cent., forming silicon iron. It is supposed by some to exist in iron in combination and in the graphitic state, but as yet no absolute proof of the latter form has been obtained. It diminishes the power of carbon to unite with iron, and tends to cause the separation of carbon as graphite, especially when the metal is slowly cooled from a white heat. It increases the fusibility and fluidity of iron. It is known that the addition of silicon to molten steel is useful in preventing the formation of blow-holes when the metal is solidifying. Probably the silicon acts in promoting the solubility of the gases in iron until the metal has actually set. In the case of pig iron, Turner[1] has shown that the maximum resistance to traction, bending, and crushing is attained by proportions of silicon varying from 1·5 to 3 per cent. Pig iron containing 2 to 3 per cent. of silicon is softer than the rest of the series, hence silicon iron is used in admixture with other brands of pig iron in the foundry to produce soft grey castings. Pig iron, with a certain amount of silicon, is necessary for the Acid Bessemer process, as by far the greater part of the heat

[1] *Jour. Chem. Soc.*, 1885.

required for the conversion must come from the silicon contained in the iron. The higher the percentage of silicon the hotter the charge, but the longer the process and the greater the loss. On the other hand, too low silicon causes cold heats, heavy skulls, and bad working generally. In the case of the open hearth, silicon is a costly fuel. Here the producer gas can be more economically applied for producing the requisite heat. So much is this appreciated in the United States that steel makers prefer the silicon in the iron to be as low as possible. They maintain that a short desiliconising period, while in many cases reducing the duration of the heat, in no way influences the quality of the product. To obtain a jacket of slag, it is better economy to add flux than to oxidise such out of the iron. High silicon in iron, therefore, increases loss and cost. Unfortunately, iron low in silicon is generally too high in sulphur, which seems to show that high silicon has the beneficial effect of preventing sulphur from uniting with iron.

Silicon appears to form with iron a number of different compounds, and the great chemical activity of silicon would indicate why graphite silicon is not found in iron. Moissan has prepared in the electrical furnace iron silicides by direct combination, and in other ways the compounds FeSi and Fe_2Si have been prepared. Carnot and Goutal[1] have studied the condition of silicon in steel. They find that when ferro-silicon containing manganese is subjected for a fortnight to the action of dilute cold sulphuric acid of about 5 per cent. strength, a complex residue results, which consists chiefly of carbon, various silicides, and hydrated silica, this being probably formed from the decomposition of certain silicides. If this residue is treated with hot dilute caustic potash, the hydrated oxide and the

[1] *Comp. Rend. de l'Acad. des. Science*, vol. cxxvi., pp. 1240.

monosilicide of iron FeSi are dissolved, hydrates of iron and manganese with silicon remaining. If these are digested in dilute sulphuric acid, the residue washed, dried, and somewhat ignited, and finally examined with a magnet, the portion separated is found to have the composition Fe_2Si, containing 20 per cent. of silicon and 80 of iron. In metal rich in manganese the residues contain a double silicide of iron and manganese, corresponding to the formula $Si(MM'_3)$.

In the case of finely powdered ferro-manganese, the larger portion of which was not magnetic, a magnet removed about 3 per cent., which, when treated as above described, left a residue of $SiFe_2$.

Chalmet[1] observes that in the blast furnace it is only possible to make ferro-silicons containing 11 to 13 per cent. of silicon, while in the electric furnace alloys are obtained up to 50 per cent. Analyses point to all these alloys being mixtures of Fe_3Si_2 and $FeSi_2$. On solution in hydrofluoric acid Fe_3Si_2 dissolves the more readily. The residue obtained by interrupting the solution suitably is represented by the formula $FeSi_2$. Ferro-silicon is crystalline in structure, and with 25 to 30 per cent. silicon takes a good polish and has a silvery lustre. The melting point increases with the increase of silicon. These higher alloys show scarcely any magnetic properties, a further proof that there is no free iron in the alloy. As the percentage of silicon increases the solubility in nitro-hydrochloric acid diminishes, but the solubility in caustic potash increases. All these alloys strongly resist oxidising agencies, and are fairly good conductors of electricity.

With regard to the influence of silicon in steel, sufficient evidence is not forthcoming to speak with certainty of its exact effect. It has been generally considered that if the

[1] *Jour. of Amer. Chem. Soc.*, vol. xxi., p. 59.

silicon exceeds 0·2 per cent. the carbon must be kept low, otherwise the steel will be brittle. Howe states, on the authority of Forsyth, that in the Bessemer process a considerable percentage of silicon, introduced with the recarburising additions, affects the ductility and forgeableness of the steel but slightly, while the same amount of silicon, if residual, that is, if remaining in the blown steel from that originally present in the cast iron, would be fatal. Now,

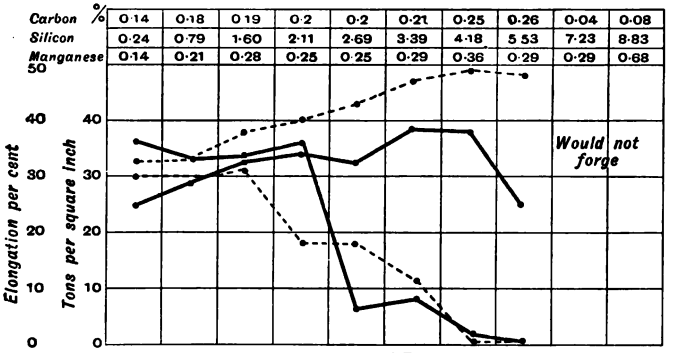


FIG. 89A.

the presence of much residual silicon indicates that the blow has been too hot, and this excessive temperature would account for the brittleness. Hadfield[1] gives the results of an elaborate series of mechanical tests on silicon steel in its forged state, which are plotted in the above diagram, Fig. 89A. In this, the upper pair of curves show the results of tensile tests in tons per square inch ; and the lower pair of curves show the results of elongation tests expressed in percentages. Apparently silicon, up to 1·5 or 1·75 per cent., although increasing the elastic strength, and raising the tensile strength, does not impair the ductility.

[1] *Introd. to Metallurgy*, Roberts-Austen, p. 33.

After this, however, the further increase of tensile strength noticed is only obtained by a serious loss of ductility. There appears to be no sharp line of demarcation, but when 1·75 per cent. is exceeded, further slight increases cause great changes in the characteristics of the metal. In this respect, therefore, its action rather resembles that of carbon than that of manganese, of which larger amounts are required to effect similar changes. In the case of mild steel, it would appear that the presence of silicon increases the tensile strength, but lowers the elastic strength. It is evident, however, from Fig. 89A that when the amount of silicon in mild steel exceeds 2 per cent., the extensibility rapidly diminishes. It may be remarked that larger additions of silicon do not cause a return of strength, which is so remarkable in the case of manganese steel. Silicon steel is, however, still magnetic with considerable percentages of silicon, and is in this respect unlike manganese steel. Hopkinson found the electrical resistance of silicon steel to be about six to seven times that of pure iron, and Hadfield has shown that the influence of silicon closely resembles that of aluminium.

Wahlberg[1] states that on calculating the average values of elongation and ultimate stress in unhardened specimens of steel containing 0·45 and 0·014 per cent. of silicon respectively, the elongation of the former is 30 per cent., with a tensile stress of 45·7 kgr. per square mm., and the latter is 31·6 per cent. elongation and tensile stress 41·2 kgr. per square mm. Evidently this difference is not remarkable when considering the great difference of silicon. Nor is there any more considerable divergency to be noted with regard to the corresponding values to be obtained by the respective series of hardening tests, although this constituent is always tending to increase the tenacity up to a

[1] *Jour. Iron and Steel Inst.*, No. 2, 1901.

certain point, while increasing the hardness. Wahlberg further states that the rather high percentage of silicon in the steels he tested gave admirable results, and that silicon does not exercise an injurious influence on the hardening results. The explanation of this seems to be that silicon, being rather easily oxidised, will gradually deteriorate a steel when repeatedly hardened, but will do no harm in the case of a single hardening.

Campbell has calculated the heat of formation of silicide of iron in the compound Fe_3Si, and that of the corresponding carbide. The values obtained for the heat of formation of carbide and silicide of iron explain readily why silicon displaces carbon from its compounds with iron, causing the carbon to assume the graphitic form in cast iron: for the reaction $Fe_3C + Si = Fe_3Si + C$ would evolve $26136{\cdot}5 - 8494 = 17642{\cdot}5$ calories.[1]

Silicon promotes soundness in steel castings by preventing the formation of blowholes, and by reducing iron oxide, and thus indirectly preventing red-shortness. It is generally considered necessary to have a small quantity of silicon in steel, otherwise the steel cracks in rolling. That this is so in many cases must be admitted, but Howe states that in American Bessemer practice the silicon in the finished steel is rarely above 0·02, the carbon from 0·1 to 0·12, and the manganese from 0·3 to 0·4 per cent. Such steel is rolled into thin plates. Silicon prevents blowholes by promoting the solubility of gases in the solid steel, and by reducing a part of the iron oxide, combining with the remainder of the oxide to form a fusible iron silicate, which is removed as slag.

Silicon indirectly retards the oxidation of iron in the Bessemer and similar processes, and the same remarks apply to carbon; thus it restrains the formation of carbonic oxide

[1] *Jour. Iron and Steel Inst.*, No. 1, 1901.

and carbon dioxide, and the ebullition that their escape causes, which in itself hastens oxidation by increasing the surface exposure. Its influence on the solubility of carbonic oxide in iron may contribute to these phenomena.

Steel and Phosphorus.—Phosphorus is capable of uniting with iron in all proportions up to about 42 per cent. Dr. Percy has shown that several compounds of phosphorus exist, having the formulae Fe_6P, Fe_3P, Fe_2P, Fe_4P_3, Fe_5P_4, FeP, and Fe_3P_4, respectively; the latter containing 57·54 per cent. of iron and 42·46 per cent. of phosphorus. This element is therefore readily taken up by iron, especially at high temperatures and under deoxidising conditions, being generally obtained from acid phosphates and silico-phosphates. On the other hand it is readily removed from iron, especially under oxidising conditions, and in the presence of strong bases, as well as by certain fluxes, such as carbonate of soda, nitre, and fluorspar. The removal of phosphorus from iron is readily effected by basic slags in the puddling process, and in the basic Bessemer and open-hearth processes.

The amount of phosphorus present in steel is seldom over 0·1 per cent., but even this small amount is only permissible in steel where the amount of carbon is low, as in the case of mild steels. It is very probable that phosphorus exists in steel as a fusible phosphide, for on polishing and etching a sample of steel containing over 0·1 per cent. of phosphorus one part darkens relatively more rapidly than the other, and if the dark and light portions are drilled out and analysed it is found that the dark portions are rich in phosphorus, while the light portions are nearly free from phosphorus. If such a sample be strongly annealed for some hours the segregation of the phosphide is very marked, and will reveal itself, after polishing and etching in iodine solution, as dark spots irregularly distributed over the

bright groundwork of iron. If steels containing notable amounts of phosphorus are treated with dilute hydrochloric acid, a portion of the phosphorus will pass off as H_3P, and generally, the freer they are from carbon the greater is the quantity evolved. With high phosphorus and moderately high carbon there is but little of the former removed.

While in ingot metal the phosphorus probably exists exclusively as a phosphide, in weld metal, such as wrought iron, it exists both as phosphide and phosphate, the latter being in the slag. There is reason to believe that the chief phosphide in iron and steel is the compound Fe_3P. The presence of phosphates in weld metal only slightly affects its properties, because they exist in the slag. When such metal is treated with hydrochloric acid the phosphorus is not volatilised as H_3P, but remains in the insoluble residue. It is therefore only in proportion as the phosphorus exists in steel and iron as phosphide that it materially influences the properties of the metal. In ingot metal little, if any, phosphorus can be present as phosphate, hence phosphorus is much more injurious in ingot than in weld metal.

The mode of occurrence of phosphorus in steel is of the highest importance, because of the influence it exerts on the physical properties. As the phosphide already referred to is readily affected by dilute acids, it follows that it tends to be removed in a different ratio to that of the iron and consequently to produce pit-marks. This is partly the cause of the occasional rough surface on steel which has been subjected to considerable mechanical treatment, such as in the manufacture of thin mild steel tubes. During the processes, such tubes require to be pickled after the several annealings, and if the temperature of annealing in any of the processes be too high or too prolonged the segregation is intensified and the subsequent pickling reveals a still rougher surface.

Howe[1] states that when phosphorus is above 0·12 per cent. in steel it has no constant effect, for if it had, the analysis of statistics should yield concordant results. Phosphorus generally raises the elastic limit, and thus the elastic ratio, which is an index of brittleness; indeed the elastic limit and breaking stress occasionally coincide. An illustration of the vagaries of phosphorus in steel may be indicated by the following: Weld iron rails often have 0·45 per cent. of phosphorus, and Bell gives one with 0·67 per cent. American rails, with 0·3 to 0·4 per cent. of carbon, rarely have more than 0·16 per cent. of phosphorus, and some less than 0·09 per cent. Some of these rails will stand a drop test of 30 feet, while others will not support a drop of 6 inches without failing. Certainly anything over 0·1 per cent. of phosphorus is dangerous. Boiler plate steel should not have more than 0·05 per cent. of phosphorus, yet some plates with 0·07 per cent. behaved admirably. In fact the behaviour of phosphorus is so capricious that it is only safe to have the smallest possible quantity in steel that has to be subjected to severe work, such as drawing, punching, and flanging.

Cutting tools should be as free as possible from phosphorus, certainly not more than 0·03 per cent. The superiority of Swedish steel is attributed to the low content of phosphorus. The ductility of steel is diminished by the presence of phosphorus, but the toughness under shock is diminished to a still greater degree, hence phosphoric steels are unfit for purposes where this property is important. The influence of even 0·01 per cent. is perceptible. The effect of phosphorus is the more severe the higher the carbon, so that with 0·1 per cent. of phosphorus and 0·1 per cent. of carbon the steel will work fairly well, but if the steel contain 1 per cent. of carbon then even 0·01 per cent. of

[1] *Metallurgy of Steel*, p. 68.

phosphorus will affect its working properties, and 0·1 per cent. in such a high carbon steel would be fatal to ductility.

With regard to welding it is a well-known fact, that in puddled iron bars phosphorus increases the tenacity, reduces the property of drawing out under tension, and increases the liability to break under shock. It, however, makes the iron weld easily, iron free from phosphorus being much more difficult to weld than iron containing phosphorus, but this property is greatly discounted, by the metal at the weld being left in a more or less coarsely granular state and being more easily fractured. Iron containing little or no phosphorus can always be obtained in a finely granular state by heating to about 900° C., when, no matter how brittle and coarse grained it was previously, its structure will become fine. With iron containing a notable amount of phosphorus no such effect is produced, it remains coarse grained, and the only method of making such steel fine in structure is by forging or rolling at a comparatively low temperature, but if the phosphorus is high, working fails to produce a fine structure. Stead states that the hardness of iron steadily increases with each addition of phosphorus, until, when it is saturated with carbon, and contains 1·7 per cent. of phosphorus as phosphide, it takes a well-hardened steel drill to drill it properly, and it apparently has a hardness of 5·5 on Mohr's scale; that is, it will scratch apatite but is itself scratched by felspar.

It is probable that in steel containing phosphorus, when in the fluid state, there exists a compound solution, intimately mixed, of carbide and of phosphide of iron in iron, and that the *carbide* solution is the more persistent, taking what iron it requires, leaving what is in excess for the phosphide, which forms a more or less concentrated solution with it, the extent of the concentration depending

on the quantity of carbon present. When the steel solidifies, the two solutions become solid solutions. On cooling through the critical point Ar_1, the carbide separates, leaving ferrite, and ferrite more or less saturated with Fe_3P. This is in accordance with the fact that steels with high carbon are more embrittled by phosphorus than those with low carbon. If free phosphide is liberated in hard steels it forms meshes round the grains, and materially reduces the strength of the mass. If phosphide is present in low carbon steels it tends to segregate, and that part of the steel is more likely to give way under sudden stress.[1]

Campbell and Babcock have investigated the condition of phosphorus in the same steel when annealed and when hardened. They dissolved the steel in a slightly acid solution of mercuric chloride, and determined the amount of phosphorus which remained in solution. Three steels were examined, containing 0·1, 0·37, and 1·22 per cent. of carbon, and 0·12, 0·16, and 0·098 per cent. of phosphorus respectively. The following results were obtained:

1. Steel with 0·1 per cent. carbon. Annealed. Phosphorus – 0·099. Quenched at 825°C. – 0·079.

2. Steel with 0·37 per cent. of carbon. Annealed Phosphorus – 0·137. Quenched at 827°C. – 0·066.

3. Steel with 1·22 per cent. of carbon. Annealed. Phosphorus – 0·098. Quenched at 825°C. – 0·018.

Thus in the mild steel the phosphorus is soluble in the annealed state to the extent of 83·2 per cent., and in the hardened state to 66·4 per cent. In the medium steel, in the annealed state to the extent of 85·6 per cent., and in the hardened state to 41·2 per cent. In the hard steel, in the annealed state to the extent of 100 per cent., and in the hardened state to 18·3 per cent.[2]

[1] *Jour. Iron and Steel Inst.*, No. 2, 1900.

[2] *Jour. of Amer. Chem. Soc.*, vol. xix., No. 10, 1897.

The action of phosphorus in iron during the cementation process has been investigated by Mr. Stead. He employed a bar of metal from the basic converter, containing 1·16 per cent. carbon and 0·6 per cent. of phosphorus. Microscopic examination of this bar after conversion proved that, except at the external parts, no free phosphide was present; the carbon being greatest at those parts, it was natural to expect free phosphide there if anywhere.

A puddled bar of iron containing 0·5 per cent. of phosphorus was also tested. A similar result was observed to that of the former trial. These two metals were then separately melted in magnesia-lined crucibles, and cooled slowly, when the phosphide separated as follows:

In the basic bar, as free phosphide, Fe_3P, 0·27 per cent., and in solid solution 0·36 per cent. In the puddled bar, as free phosphide, 0·21 per cent., and in solid solution 0·29 per cent.

The effect of phosphorus is to produce a coarsely crystalline structure in iron and steel, but in the process of cementation the structure is entirely altered, except perhaps that of a small core in the centre. The external portions after conversion are coarsely granular, but between these and the core the crystalline masses are arranged in columns. It is evident that, as the carbon passes into the iron its dominating influence throws out the phosphide and causes a complete re-arrangement of the structure.

Steel and Sulphur.—Iron is capable of taking up sulphur in various proportions, the maximum amount being found in the compound FeS_2. Except when the sulphur is present in minute quantities, it exists in iron and steel as a chemical compound, of which there are several different forms. If we consider that other elements are also present, such as silicon, manganese, carbon, etc., most of which are capable of combining with sulphur, it will be seen how complicated

the effect may be. This may account for the vagaries of sulphur in different samples of iron and steel. For example, Turner obtained a compound having the formula Fe_4SiS, by introducing sulphur into molten silicon pig iron. This compound has a beautiful, bright, crystalline appearance, with large faces, and is very brittle, so that it can be easily powdered in a mortar, yielding bright and light scales. This scaly appearance has probably led other observers to suppose it to be graphitoidal silicon.

Many facts seem to point to the existence of sulphur in iron and steel in the form of chemical compounds, dissolved or suspended in the general mass in particles, often too small to be seen even by the microscope, but when present in large quantities, as in the case of cast iron, they strongly tend to segregate along with other impurities, and often to liquate out. Sulphur is readily absorbed by molten steel from gases containing that element, as well as from solid sulphides and sulphates. Campbell has shown, by exposing a bar of Bessemer steel to a temperature of about 1200° C., in contact with oxy-sulphide of iron and manganese, that the sulphide had diffused completely into the iron. The experiments were conducted both in an oxidising and in a non-oxidising atmosphere, but only in the former was the diffusion complete. The temperature of the bar seems to have a marked influence on the diffusion, for when the bar was raised to 1100° C., the diffusion was very slight, complete diffusion not taking place until 1200° was reached. Prof. Arnold has also shown that ferrous sulphide is capable of diffusing through highly heated iron.

With regard to the presence of sulphur in iron Sir Lothian Bell states that, in the blast furnace, a low temperature favours the union of sulphur with iron, and that the composition of the slag greatly influences the sulphur absorption. It is generally observed that the amount of

sulphur in pig iron increases with an increase of combined carbon, but as this increase is chiefly in consequence of the diminution in the amount of silicon, it would indicate that silicon tends to prevent sulphur uniting with iron. It is usual to attribute the presence or absence of much sulphur in iron to the degree of temperature in the furnace; assuming that a high temperature expels sulphur. But a high temperature is the condition for reduction of silicon, which passes into the iron, and the latter may be the cause of the lowness of the sulphur, for when silicon is high, sulphur is low, and *vice versa*. If pig iron rich in silicon is melted in a cupola the product is found to be low in sulphur. If pig iron high or low in silicon is melted in a cupola at a low temperature a greater quantity of sulphur is in the product than when a higher temperature is employed.

It has been stated that sulphur exists in iron chiefly in the form of chemical compounds (sulphides), and as these sulphides are moderately fusible they are liable to retain the liquid form after the mass of the metal has become solid. Now it is well known that sulphur, like other metalloids in iron and steel, tends to segregate in the middle and upper part of a cooling ingot; for being specifically lighter it tends to ascend. If such an ingot is hammered and rolled, the segregated impurities will be found in the middle portions of the bar or sheet and if the sulphur and other impurities are abnormally increased, objectionable seams occur in the finished plates. The larger the ingot the more frequently are these seams found in the plates made from them. Prof. Arnold prepared a sample of practically pure iron to which he added about 1 per cent. of sulphur. On microscopic examination he found it to consist of large crystals of one type, through which the sulphides of iron were fairly evenly distributed, but which possess an extraordinary power of individual contraction, the result being that large

fissures were developed between the joints in such numbers that the metal was almost cut in pieces. In some instances actually detached crystals were observed, and during a compression test many such fell out in the form of dust. It is extremely improbable that the inter-crystalline spaces in cold steel, when due to the presence of sulphur, will weld up on heating, hence the red-shortness produced by the presence of notable quantities of this element.[1]

Sulphur has the specific effect of making iron exceedingly brittle at a red heat and of destroying its welding power. Its effects are generally most marked at a dull-red heat and irons that crack at that temperature, due to the presence of sulphur, may work very well at a higher temperature, and at the same time be quite malleable when cold. If, however, the sulphur is abnormally high the iron is not malleable at any temperature above a red heat. Manganese counteracts the evil effects of sulphur, and as manganese is invariably present in steel it thus exerts a beneficial influence on the steel.

The red-shortness of steel, due to sulphur, diminishes its tensile strength and ductility. This is naturally to be expected, as the fusible sulphides tend to produce inter-crystalline weakness by breaking the continuity. In moderate quantity sulphur may make weld-iron tougher, but it probably has the opposite effect on ingot-metal.

Steel and Manganese.—Manganese is so intimately associated with iron in nature that few iron ores are free from that element, consequently nearly all commercial iron and steel contain manganese. It appears to unite with iron in all proportions, but being more oxidisable than iron, it more readily unites with oxygen, and, being a powerful base, passes into the slag. In consequence of this superior affinity for oxygen it retards the oxidation of the iron in

[1] *Jour. Iron and Steel Inst.*, No. 1, 1894.

operations such as puddling, Bessemerising, and open-hearth methods of making steel. It also appears to volatilise to some extent in these operations. It increases the solvent power of iron for carbon at high temperatures, and prevents the separation of graphite at lower ones, thus making the iron white, crystalline, and hard. In the refining of iron, manganese prevents loss of iron from oxidation, and assists in making a more fusible slag. By preventing ebullition during solidification and keeping gases in solution it tends to promote soundness in castings. It counteracts the bad effects of sulphur, and this, together with its power of reducing oxide of iron, prevents red-shortness. It does not counteract the cold-shortness caused by phosphorus. These valuable properties render it an indispensable element in most modern methods of steel making. The highly esteemed properties of Swedish steel are partly due to the presence of some manganese.

The relations of manganese to oxygen are of considerable importance in steel making. Manganese is reduced from its oxide at a white heat, while silica is unaffected, showing that manganese has a lower affinity for oxygen than silicon, yet because its combination with iron is weaker than that of silicon, the manganese is more readily removed from iron in the open-hearth method of making steel; also its active slag-forming tendencies often cause the reduction of silica from the acid linings of furnaces and crucibles. Not only does the presence of manganese prevent oxidation of iron when in the molten state, but also prevents oxidation of iron, and therefore red-shortness, in solid steel during the operations of forging and welding. Because of this power of manganese to remove oxygen, this metal is generally added to oxygenated metal, at the end of the refining stage, in the Bessemer and open-hearth methods of steel making.

Sulphur is well known to be injurious to steel, and as this element is invariably present in varying amounts, especially in pig iron, its removal is a matter of prime importance. It has been shown that manganese has great slag-forming tendencies, and being a powerful base, forms basic slags. Now the more basic the slag the more completely is the sulphur removed in the slag, and therefore the less will be the amount left in the iron, hence the great efficacy of manganese. Massenez has devised a process of desulphurisation of iron by mixing pig iron high in manganese with pig iron high in sulphur, by which means sulphide of manganese is formed, which rises to the surface of the molten metal in virtue of its lower specific gravity. 2·6 parts of manganese remove 1 part of sulphur. Besides removing sulphur from iron, manganese counteracts the effects of that which remains, probably by forming sulphide of manganese and remaining mechanically mixed with the iron.

Howe states that, on the average, the net effects of manganese on tensile strength are slight. The fact that rails with 1·5 per cent. manganese and 0·35 per cent. carbon often successfully pass the straightening press, indicates that, if manganese renders steel brittle under shock, this effect is either slight, or exceptional, or non-cumulative.

Our knowledge of the alloys formed by these metals has been greatly increased within the last few years by the labours of Mr. R. A. Hadfield of Sheffield. Iron readily unites with manganese, and when the proportion of the latter metal is considerable, the alloy is very hard, whiter, more fusible, and much more brittle in character than iron. Steel containing from $2\frac{1}{2}$ to 7 per cent. of manganese is brittle and comparatively worthless, but when the amount exceeds 7 per cent., alloys possessing very great strength

and toughness are obtained.[1] The weakness of the low percentage alloys may be understood from the following tests made by Mr. Hadfield. Cast-bars $2\frac{5}{8}$ inches square and 30 inches long, supported on bearings 2 feet apart, were broken by hydraulic pressure. One specimen containing 0·37 per cent. of carbon and 4·45 per cent. of manganese was fractured by a pressure of $3\frac{3}{4}$ tons, whilst a bar of ordinary cast-iron stood 12 tons, and bars containing 17 and 20 per cent. manganese stood a pressure of $29\frac{1}{2}$ and 38 tons respectively. A cast bar containing 4·73 per cent. manganese, when dropped from a height of 3 or 4 feet on to a cast-iron floor, broke in two or three places. A sample containing 0·48 per cent. carbon and 4·9 per cent. manganese, though very ductile while hot, could be reduced to powder by a hand-hammer when cold, little or no cohesion seeming to exist between the particles. On the other hand, a specimen of forged material, containing 13·75 per cent. manganese and 0·85 per cent. carbon, when water toughened, had a tensile strength of 65 tons per square inch, with 50 per cent. elongation; another specimen had a strength of 69 tons, and 46 per cent. elongation. The strongest alloy contains about 14 per cent. of manganese.

When manganese-steel is plunged into water no hardening effect takes place like that of ordinary steel, but the metal containing upwards of 7 cent. of manganese acquires increased tenacity and toughness. From a large number of tests it has been found that the higher the temperature to which the alloy is raised, and the more suddenly the cooling takes place, the higher is its breaking stress, and the greater its toughness and elongation. The influence of water quenching on manganese-steel is strikingly shown in alloys required to be drawn into wire. If it be attempted to

[1] Hadfield, Paper on "Manganese Alloys," *I. C. Eng.*, 28th February, 1888.

draw hammered or rolled rods into wire without a previous heating and quenching it will not draw at all, and ordinary annealing makes no difference to it. If, however, it be raised to a yellow heat and then plunged into cold water it can be readily drawn into wire. After reducing the wire two numbers of the gauge, the metal must be again heated and plunged into water. By this means it may be drawn to any reasonable degree of fineness.

Mukai examined chemically and microscopically two samples of manganese steel, containing respectively 12·3 and 10·6 per cent. of manganese, and for comparison, a third sample containing 0·6 per cent., in order to discover the reason for the toughening that occurs on sudden cooling. It is found that the specific gravity of manganese steel in the quickly cooled state is apparently greater than in the slowly cooled state, whilst the opposite generally holds true for other metals. The hardness is also much greater in ordinary steel by sudden cooling. The percentage of cement, or non-hardening carbon, is rather large in manganese steel. This is partly due to the manganese present, which increases the solubility of carbon in iron. The characteristic features in the structure of manganese steel are the parallel dark plates on its surface, surrounded by other masses. This is often seen in iron rich in manganese, but not in ordinary steel. The size of the grains, although variable in the suddenly cooled steel, are larger than in the slowly cooled samples, while the grain in ordinary steel is finer. The ductility and malleability of suddenly cooled manganese steel cannot be attributed to the carbon, as that behaves as in ordinary steel, in remaining as hardening carbon on quenching. The ductility may be ascribed to the molecular condition, but it is uncertain whether it is due to manganese or not.

It has been pointed out that when steel is cooled slowly,

certain critical points are observed, due to evolution of heat, and that these points indicate a change in the allotropic condition of the iron. It is very noticeable that in manganese steel no such break in the regularity of cooling takes place, hence the steel remains hard. There is another point of evidence connected with the presence of manganese as regards molecular change. Red hot iron is not magnetic, and, as the range of temperature within which iron is said to be in the alpha form practically coincides with the disappearance of magnetism, beta iron is non-magnetic. Manganese steel is non-magnetic, therefore the iron alloyed with the manganese is in the beta form. Ewing states that "no magnetising force to which the metal is likely to be subjected, in any of its practical applications, would produce more than an infinitesimal amount of magnetism in Hadfield's manganese steel. When the amount of manganese is small it simply retards the passage of beta to alpha iron."

The density of manganese steel is a little higher than that of ordinary steel. In its ordinary condition it is very hard and easily scratches steel that is not of a high temper. When the manganese exceeds 20 per cent. the alloy is practically non-magnetic. Dr. Hopkinson found that the maximum magnetisations of wrought-iron and manganese steel (with 12·36 per cent. of manganese) are as 258 to 1. It shows no elongation under the magnetic influence.

Manganese steel does not exhibit the anomalous expansion and "after-glow," termed *recalescence*, which takes place in magnetic metals when they cool to a certain critical temperature, after being heated to whiteness. A Sheffield firm reported that in rolling a considerable length of manganese steel, the finer it became the more it retained its heat, in fact, it appeared to gather heat in the process.

Ferro-Manganese is a variety of metal especially manufactured in a blast furnace from ores rich in oxide of manganese, and is very extensively used in the manufacture of mild steel. When the pig-iron contains less than about 20 per cent. manganese, its fracture shows large crystalline cleavage planes, and it is then termed spiegel-eisen. Ferro-manganese is a hard crystalline body, but the fractured surface does not present the large cleavage planes so characteristic of spiegel-eisen. It contains from 25 to 85 per cent. of manganese.

From the thermo-chemical researches of Troost and Hautefeuille [1] there are strong grounds for believing that manganese forms with carbon and silicon chemical compounds of considerable stability. They established the fact that while iron forms with carbon and silicon endothermic compounds, manganese forms with these elements exothermic compounds. They regard the manganese compounds in the nature of salts, and the iron compounds in the nature of solutions. Manganese differs from iron in having a much higher solvent power for carbon; by solvent power being meant the capability of forming those indefinite solution compounds, truly chemical in nature, but readily passing from one form to another, and uniting in varying proportions to form compounds strictly limited by the law of definite and multiple proportions. In addition, manganese evidently forms compounds strictly limited in composition, as shown by the sharply defined crystalline form. In both ferro-manganese and spiegel-eisen a ternary compound is present, probably having the formula MM'_8C, in which M represents manganese and iron in isomorphous compounds. As the manganese is gradually increased in iron, the platy forms, so characteristic of spiegel-eisen, pass into the acicular structure of ferro-manganese.

[1] *Ann. de Chimie et Phys.*, vol. ix., p. 56.

Steel and Arsenic.—Arsenic is a widely distributed element, and occurs in many iron ores, from which it gets into the iron obtained from such ores. When the quantity in the ore is large the greater part is removed in calcining, but a residue remains. When the ore is rich in manganese, practically all the arsenic present is concentrated in the pig iron. However, the quantities found in ordinary pig iron are very small, but practically the whole of the arsenic present passes into the steel, made in the open-hearth or Bessemer, whether acid or basic mode of working is adopted. Pattinson and Stead state "that as arsenic and iron combine to form arsenide of iron, which is extremely brittle and fusible, corresponding in these respects to phosphide of iron, there can be little doubt that the tendency of arsenic must be to weaken material in which it is present. When in iron in very small quantities, it is practically all present in a separate form as arsenide of iron, and not combined with the general mass, as in the case of phosphorus. On solution of arsenical steel in dilute hydrochloric or sulphuric acid, the arsenic remains as a black powder. We, on that account, incline to the belief that it cannot be so injurious as phosphorus, and will be analagous in its effects to that of carbon in soft annealed steel, in which it exists as a free carbide."

Harbord[1] has studied the effect of arsenic on steel by making alloys containing from 0·07 to 1 per cent. of arsenic, and submitting them to mechanical tests. Those up to about 0·1 per cent. rolled perfectly, the others fairly well. Although the samples did not show the usual signs of red-shortness, all above 0·1 per cent. of arsenic showed surface cracks, which in many cases extended so deeply as to necessitate turning down to a smaller area before they could be tested for tenacity. Those not exceeding

[1] *Jour. Iron and Steel Inst.*, No. 1, 1888.

0·17 per cent. do not appear to affect the bending tests in the cold, but above this percentage cold-shortness begins to appear, and with 1 per cent. of arsenic the metal is very brittle. With regard to welding arsenic is objectionable, the influence being perceptible with 0·1 per cent., and with 0·5 per cent. the bars were unweldable. The tenacity is considerably increased by arsenic up to 0·66 per cent., and above this the metal is brittle. Arsenic lowers the elastic limit of steel, and decreases elongation and reduction of area. It makes steel considerably harder by sudden quenching from a red heat.

Steel and Chromium.—These elements have a strong affinity for each other and appear to unite in all proportions. Chrome iron ore is somewhat abundant in nature, and when such an ore is submitted to a reducing influence at a high temperature both the iron and the chromium are reduced and form an alloy. Berthier states that when a mixture of oxide of iron and oxide of chromium is strongly heated in a carbon-lined crucible, both oxides are completely reduced, and a perfectly homogeneous combination of the two metals is obtained. The alloys are generally hard, brittle, crystalline, and of a greyish-white colour, having considerable lustre: they are less fusible, less magnetic, and less soluble in acids than iron: the characteristic features are more prominent in proportion to the amount of chromium present.

In 1820 Faraday produced two specimens of chrome steel, which he said forged well, and were as malleable as pure iron, and both gave a very beautiful damask when rubbed with sulphuric acid. From these results as to malleability, and also from the mixture used, the percentage of chromium must have been small. This "damascening" of chrome steel is interesting when we consider that it is not producible with ordinary steel, and that it is only

otherwise produced by taking great precautions in the working of the purer forms of malleable iron. Schneider has shown that chrome pig iron is not a homogeneous body, and the fact of damascening of the steel would indicate that the same observation applies to it.

Burstlien of Unieux commenced the manufacture of chrome steel in 1875. He produced his ferro chrome in crucibles and added a certain proportion of this rich alloy to the steel. The usual specimens of ferro-chrome contain from 40 to 50 per cent. of chromium. The metal is cast into iron moulds and chilled. The following table shows the composition per cent. of different samples, and it is interesting to notice the large amount of carbon taken up:

Chromium, -	80	60	52	42	25	18	16	12
Carbon, - -	11	9·5	7·8	7·3	6·7	6·2	2·7	2

The remainder is iron and silicon, the latter sometimes exceeding 2 per cent. The hardness and brittleness increase with the proportion of silicon and carbon. When ferro-chrome is cooled slowly it crystallises in a mass of needle-shaped crystals, which are more apparent when the carbon is low. The fracture of ferro-chrome resembles that of white cast iron, when the percentage of chromium is from 12 to 20 per cent., and the brilliant white radial needles are of considerable length, but as the chromium increases they become shorter and thinner, and with 50 per cent. the alloy is granular.

Chromium, even when alloyed with iron, is very readily oxidised. In puddling chrome pig iron the chromium is largely oxidised and removed in the slag, which is made very thick by its presence. In the Bessemer process, chromium is not so readily removed. The readiness with which chromium oxidises has suggested the use of ferro-chrome in the Bessemer process instead of ferro-manganese, but chromium oxide is well nigh infusible and

by remaining in the steel would break its continuity, and thus impairs its welding properties. In welding chrome steel a strong and adherent scale forms during the heating which tends to prevent cohesion. Also in virtue of the ease with which chromium oxidises, chrome steel is very liable to rust. Hadfield found that ferro-chrome with 8 to 28 per cent. of chromium is readily attracted by the magnet, that an alloy with 44 per cent. is but slightly attracted when in bulk, but is strongly attracted when in small pieces or in powder: that an alloy with 66 per cent. of chromium is not attracted when in bulk, but is slightly attracted when in powder.

Chromium does not appear to increase the tensile strength of steel, at any rate with the small quantities usually present in steel, neither does it raise the elastic limit. The percentage elongation is diminished, so that chromium does not increase either the strength or toughness.

From the remarks made with regard to the high fusibility of chromium and the difficultly scorifiable nature of its oxide, it will be easily understood that chromium is not calculated to promote soundness in casting, so that in this respect it differs from silicon and aluminium. Hadfield considers that 3 to 4 per cent. of chromium in steel would not confer freedom from honeycombs, so that in chrome steels it is as necessary to add aluminium or silicon to ensure soundness as in ordinary steel.

With respect to hardness it does not appear that chromium alone has the power of hardening iron, but in the presence of carbon the chromium seems to act as a kind of spur to the carbon and tends more forcibly to drive the latter into the hardening form and to keep it in that state. If this is the case, it is easily understood how the hardness of chrome steel increases with an increase of chromium, seeing that the carbon also tends to increase in the same ratio.

In the manufacture of steel varying proportions of chromium may be used. Burstlein states that steel containing 2 per cent. carbon and 12 per cent. chromium can be forged. It is very difficult to weld chrome steel, as might be anticipated from the easy oxidisibility of chromium. One of its chief uses is in the manufacture of shells for armour piercing projectiles, which contain from 1·2 to 2 per cent. of chromium, and carbon varying with the desired degree of hardness required.

According to Osmond,[1] it appears that chromium in iron interferes with the crystallisation of the iron to a considerable extent, in this way modifying the structure, (1) by the absence of pearlite; (2) by the absence or diminution of the granular structure. The effect of chromium in steel is not at all proportional to the amount of chromium the steel contains, as small amounts are relatively more active than larger ones. As the amount of chromium increases, a compound of chromium, iron, and carbon is formed, which is only partially attacked by acids, and possesses great hardness. The absence or diminution of the size of the grain probably plays an important part in the modifications that chromium effects in the mechanical properties of steel. Chromium appears to exist in steel in three states, either separately or simultaneously. (1) In the state of dissolved chromium. (2) In the state of a very hard triple compound of iron, chromium, and carbon, in the form of isolated globules. (3) Also in the same condition in the form of a solidified solution. The above-mentioned triple compound when incorporated with a more malleable matrix, naturally communicates to it a certain degree of hardness, combined with the relative plasticity of the matrix itself.

The relative differences of hardness or softness of the two main bodies forming steel, determines the wear and tear of

[1] *Jour. Iron and Steel Inst.*, No. 2, 1892.

steel to a great extent. The predominance of the soft body or matrix has a good deal to do with the behaviour of the steel. The crystals, their hardness and number, evidently give strength and elasticity to steel, and when these hard crystals are wanting we have a metal of low strength and high ductility. On the other hand, if the hardness of the matrix approaches that of the hard crystals we have a stiffer metal with still good ductility. The fine structure of chrome steel indicates shock-resisting qualities with high strength.

The magnetic resistance of chrome steel with less than 10 per cent. of chromium is high. The coercive force, when the metal is hardened is great, and it should therefore make good permanent magnets. Annealing has a marked effect in diminishing the coercive force. Chromium has a much less effect in destroying the magnetic properties of the iron with which it is alloyed than has manganese.

The electrical resistance of chrome steels, with up to 10 per cent. of chromium, is high, but probably not so high as that of manganese steel; the resistance is materially increased by quenching.

Steel and Nickel.—These metals unite to form a series of alloys, which of late years have received an enormous amount of attention, and, although the most recent productions contain small amounts of other elements, such as manganese, such alloys may be considered under this heading. Faraday and Stoddard prepared alloys of iron and nickel containing 3 and 10 per cent. of nickel respectively. They stated that the former was as malleable and could be as easily worked as pure iron. The latter was semi-ductile, very tenacious, with a granular structure, and little affected by the atmosphere. They are capable of a high polish. Bergmann states that iron and nickel unite in all proportions.

Mr. James Riley of Glasgow and Mr. Hall of Sheffield have independently given great attention to the production of iron nickel alloys, and, in a paper read before the Iron and Steel Institute in May, 1889, the following facts were stated: "The alloys can be made in crucibles, or on a large scale in the open-hearth furnace, where a charge can be worked off in about seven hours. Its working demands no special care, and the composition of the resulting steel can be easily and definitely controlled. If the charge is properly worked nearly the whole of the nickel will be found in the steel, and almost none in the slag. The metal sets steadily in the mould, it is more fluid than ordinary steel when melted, it solidifies more rapidly, and appears thoroughly homogeneous. The ingots are clean and smooth in appearance on the outside, but those richest in nickel are a little more piped than ingots of ordinary mild steel. There is less liquation of the metalloids in these ingots, therefore the liability to serious troubles from this cause is much reduced. The scrap from hammering, rolling, shearing, etc., can be remelted in making another charge without loss of nickel.

"If the steel has been properly made, and is of correct composition, it will hammer and roll well, whether it contains little or much nickel. It must be remembered, however, that in nickel steel we have present nickel, manganese, and iron, together with carbon, silicon, phosphorus, and a little sulphur, and that a difference in the quantities of these elements will influence the properties of the alloy; in other words, the degree of purity of the nickel and iron employed will modify the result, as in the case of ordinary iron and steel." The following table embodies the result of tests on various alloys made by Mr. Riley:

Tests of Steel with Varying Contents of Nickel.

No.	Composition per cent. exclusive of Iron.			Tensile Tests as Cast.					Tensile Tests as Cast and Annealed.					Tensile Tests as Rolled.					Tensile Tests as Rolled and Annealed.				
	Nickel.	Carbon.	Manganese.	Elastic limit in tons.	Breaking stress in tons.	Extension per cent. in inches. 8 in.	Extension per cent. in inches. 4 in.	Contraction of area per cent.	Elastic limit in tons.	Breaking stress in tons.	Extension per cent. in inches. 8 in.	Extension per cent. in inches. 4 in.	Contraction of area per cent.	Elastic limit in tons.	Breaking stress in tons.	Extension per cent. in inches. 8 in.	Extension per cent. in inches. 4 in.	Contraction of area per cent.	Elastic limit in tons.	Breaking stress in tons.	Extension per cent. in inches. 8 in.	Extension per cent. in inches. 4 in.	Contraction of area per cent.
1	1·0	0·42	0·58	Test-piece defective.					27·3	54·6	—	1·5	9·5	32·1	57·6	—	11·0	24·0	30·1	55·1	—	18·7	45·0
2	2·0	0·90	0·50	Too hard to machine with Mushet Steed. Makes a fine tool when tempered at a dull red heat in boiling water.																			
3	3·0	0·35	0·57	19·8	34·9	—	2·5	5·6	24·0	34·9	—	2·5	9·0	31·4	51·0	—	20·3	37·0	28·0	48·5	—	20·3	42·0
4	3·0	0·60	0·26	—	—	—	—	—	—	—	—	—	—	29·4	51·0	9·0	10·1	09·0	30·3	42·9	07·5	09·0	12·0
5	4·0	0·85	0·50	Too hard to machine with Mushet Steel. Makes a fine tool when tempered at a dull red heat in boiling water.																			
6	4·7	0·22	0·23	—	—	—	—	—	—	—	—	—	—	25·1	40·5	17·75	23·4	42·0	28·0	40·6	20·0	25·0	44·8*
7	5·0	0·30	0·30	—	—	—	—	—	—	—	—	—	—	30·0	46·4	10·0	12·5	22·5	28·0	42·6	15·0	17·5	18·5*
8	5·0	0·50	0·34	—	—	—	—	—	—	—	—	—	—	31·1	12·0	14·0	15·6	14·0	32·5	46·8	13·5	14·0	17·0*
9	10·0	0·50	0·50	Too hard to machine. Makes a good cutting tool when tempered in cold air-blast.																			
10	25·0	0·27	0·85	—	—	—	—	—	—	—	—	—	—	38·2	51·4	10·5	11·7	—	12·75	45·8	29·0	30·0	28·6
11	25·0	0·82	0·52	—	—	—	—	—	—	—	—	—	—	22·0	47·6	43·5	47·6	60·0	15·1	42·1	40·0	45·3	43·6
12	49·4	0·35	0·57	—	—	—	—	—	—	—	—	—	—	20·5	37·4	—	12·0	24·0	21·0	37·0	—	20·0	29·0

* Average reduced by one piece giving low result.

It will be seen from the foregoing table that the addition of nickel to mild steel increases the elastic limit and breaking stress considerably. In numbers 2 and 5 tests, the great hardness, partly due to the large amount of carbon, is also increased by the presence of nickel. In No. 9 test, with much less carbon, but with 10 per cent. nickel, a very hard alloy is obtained. This quality of hardness continues, as the amount of nickel is increased, until about 20 per cent. of nickel is reached, when a change takes place, and successive additions of nickel tend to make the steel softer and more ductile. With regard to the hardening effect of nickel on iron, there is some resemblance to that of manganese on steel previously described. The whole of the series of nickel-steels, up to 50 per cent. nickel, take a good polish and finish, with a good surface, the colour being lighter with increased additions of nickel.

Mr. Riley states that the steels rich in nickel are practically non-corrodible, and that those poor in nickel are less so than other steels in this respect. The 1 per cent. nickel-steel welds fairly well, but this property deteriorates with each addition of nickel.

Since the reading of Mr. Riley's paper the alloys of nickel and iron have assumed very great importance, owing to the use of nickel-steel as a material for armour plates. Nickel-steel has a lower combination of tensile strength with elongation, but a higher combination of elastic limit with elongation than manganese steel, and lacks the extreme hardness of the latter, but is still so hard that its machining is somewhat difficult. Nickel, from 1 to 5 per cent., greatly increases the tensile strength and slightly increases the elongation. With 25 per cent. of nickel the elongation is increased and the tensile strength remains about the same. The hardness depends on the amount of

nickel and carbon conjointly, but much less on the nickel than on the carbon.

Nickel steel, with 1 to 3 per cent. nickel, and low carbon, as in all mild steels, seems well adapted for structural purposes, more especially as it possesses a high elastic limit. It has been applied for boilers, for which it is admirably adapted on account of its resistance to corrosion. It can be readily forged or pressed in dies without cracking, its great ductility here showing to great advantage. Under the drop test, nickel-steel gives excellent results, and its toughness, together with its ability to resist shock, makes it well suited for armour plate. The ability to resist shock is not altogether a question of elongation, but also of toughness and tenacity. In consequence of its strength and stiffness, it has been extensively used in America for shafts, piston-rods, propellers, etc.

For armour plate, about 3·25 per cent. nickel is used with low carbon, and such material will give about 30 to 40 tons per square inch tensile strength and 20 to 25 per cent. elongation. Such plates are Harveyised, that is to say, case hardened to a depth of 1 to 1¼ inches. Mr. J. G. Eaton, speaking for the United States Navy in 1895, says "all armour plate, protective deck, as well as side and citadel plates, had been alloyed with nickel to about 3½ per cent. This alloy not only lent itself readily to press and hammer forging, but, after Harveyising, took a temper superior to plain carbon plates. In cases where the energy of the projectile exceeded the resistance of the plate, that is where the plate was attacked by a shell which exceeded in calibre the thickness of the plate, and, where its velocity was increased to the full service foot seconds, the shell passed through the plate, leaving a clean aperture, with scarcely a swelling on the face or back. The remarkable toughness of the plate was fully evidenced by the absence

of cracks, and the non-fusibility of the alloy was notable. When a crack is developed in a carbon plate, it generally extends to the nearest edge, and is always a thorough crack. With nickel-steel, small cracks, opening near the point punctured, extend but a short distance, and do not go through. The re-forging of armour plates after Harveyising, and before tempering, still further increases the resistance of nickel plates, so that it was accepted, that a 15 inch forged nickel steel plate was the equal of a 20 inch carbon plate treated to the same temper, but only simply forged. The fact that a nickel-steel plate takes a temper on the surface practically equal to that of a carbon plate, whilst the rest of the plate is composed of a tough alloy that resists cracking, renders it peculiarly adapted to armour plate purposes. In fact, low carbon steels alloyed with a small percentage of nickel, say 3 per cent., display all the properties of high carbon steels, but are practically free from their treacherous brittleness."

With regard to the welding of nickel-steel, diverse opinions have been expressed, no doubt owing to the tendency of the scale to adhere rather tenaciously to the metal, for it cannot be readily detached by tapping sideways, like that of ordinary steel. Speaking generally, steel with 1 per cent. nickel welds easily and solidly. The 2 per cent. alloy is nearly as good. The 3 per cent. acts fairly; the 4 per cent. only with difficulty, and then only partially, and above that amount practically not at all. These remarks apply to steel with about 2 per cent. of carbon; but with less carbon, the welding is probably easier. The tendency of nickel-steel to form scale, may be largely prevented by greater attention being paid to the manner of heating.

A series of exhaustive and instructive tests with nickel steel has been undertaken by the Charlottenburg Testing

Institution, near Berlin. The chemical composition of the blocks used for testing varied between 99·6 and 0·33 per cent. iron, with 0·05 to 98·4 per cent. nickel, the other ingredients, except cobalt, being very small. The tests showed that when the percentage of nickel varied from 0 to 8 per cent. the limit of elasticity increased from 9·2 to 27·9 tons per square inch, the tensile strength from 20·3 to 35·5 tons per square inch, whilst the elongation diminished from 30 to 10 per cent. The greatest strength is found with 8 per cent. nickel. With 16 per cent. nickel the tensile strength is 26 tons and the alloy is extremely brittle. With 30 per cent. the strength has gone down to 6·4 tons, and the elongation is only 2 per cent. With 60 to 98 per cent. of nickel the tensile strength ranges from 24 to 19 tons, and the elongation 36 to 17 per cent. respectively. As regards the fractured surface of the alloys the 0·5 per cent. nickel is porous, but the 1 per cent. nickel alloy is close grained. With the 3 per cent. alloy the surface is fine grained, but with increasing nickel the grain becomes coarser, eventually showing needle-shaped crystals. The alloys will only stand rolling when the nickel is below 4 per cent., and crack and tumble to pieces when the percentage of nickel is higher.[1]

Nickel steel with more than 25 per cent. of nickel is reversible as regards magnetism. On heating beyond a certain temperature the magnetic power disappears, but is regained at the same temperature on cooling. With less than 25 per cent. of nickel the alloys are not reversible, except at much lower temperatures, some even below 0° C. Others with 22 per cent. nickel and 3 per cent. of chromium, do not regain their magnetism even at the temperature of liquid air. This investigation has led to the discovery of a valuable alloy containing 35·36 per cent. nickel, of which the dilata-

[1] *Engineering*, vol. 66, p. 862.

tion is ten times that of platinum. This will probably prove valuable for meteorological instruments.[1]

Hopkinson found that nickel-iron alloys, with 23 to 25 per cent. of nickel, are about 2 per cent. less dense when in the magnetisable state than they are when in the non-magnetisable state.

Steel and Aluminium.—These metals unite in various proportions, forming hard, white, brittle alloys when the aluminium is present in notable quantity. Alloys, known as ferro-aluminium have been extensively manufactured and used for introducing small quantities of aluminium into steel and cast iron, instead of adding the pure metal. When the aluminium in the ferro-alloys exceeds a certain amount, say 17 per cent., the alloy becomes non-magnetic, and like ferro-manganese is not attracted by a magnet. Nordenfeldt, in the production of what he termed "mitis castings," added 0·1 per cent. of aluminium to wrought iron and found that it increased the fluidity, so that such metal could be used for castings. He assumed that it therefore decreased the fusing point. Osmond has, however, shown that it does not produce any considerable lowering of the fusing point. In all probability the greater liquidity is due to heat produced by chemical combination, seeing that aluminium is very active chemically and serves to eliminate oxide of iron. Mr. Galbraith has pointed out that the fluidity of molten iron and steel depends not only on the amount of heat imparted by external means, or by oxidation, but often on the quantity of intermingled slag. Steel may be overheated and yet lack fluidity.

Metallic aluminium has a strong power of absorbing gases and keeping them in solution, and if the same property prevails when aluminium is present in steel its well-known

[1] *Bull. de la Soc. d'Encouragement*, July, 1898.

power of producing soundness in steel is accounted for. Aluminium in iron tends to the formation of a coarse grain, and as the percentage is increased the crystals increase in size, and cleave like those of spiegel-eisen, which accounts for its brittleness, and this cannot be removed by annealing. As might be expected from the nature of aluminium, its crystallising tendency and strong affinity for oxygen, together with the insolubility of its oxide in the ordinary welding fluxes, it prevents steel, containing any notable quantity of it, from welding.

Aluminium, in small quantities, does not appear to confer appreciable hardness on iron either in the forged or cast state. It slightly diminishes the tensile strength and increases the ductility, hence it can be drawn into wire which possesses considerable toughness.

Aluminium in cast iron acts very similar to silicon, in that it tends to set the carbon free as graphite; to remove dissolved oxides of iron; to decompose solid and gaseous compounds of carbon and hydrogen entangled in the molten metal, and possibly also brittle combinations of carbon and iron. A very much smaller quantity of aluminium than silicon is required to do the same amount of work in promoting soundness.

The following are the proportions of aluminium generally used for iron and steel:

For Bessemer steel, - - -	0·02 per cent.
Siemens, - - - - -	0·05 ,,
Crucible, - - - - -	0·10 ,,
Cast-iron, - - -	0·10 to 0·20 ,,

These proportions may be altered to suit special cases, but 0·2 should not be exceeded for steel. The aluminium may be added to the ladle by tongs, or in a perforated iron case, fixed to an iron rod. It should be plunged sharply through the fluid metal to the bottom.

Steel and Tungsten.—These metals unite in various proportions to form valuable alloys. The general effect of tungsten is to render steel hard and brittle. The alloys are very difficult to forge, and cannot be welded when the tungsten exceeds 2 per cent. They are therefore unfit for structural purposes, and also for tools subjected to shock, such as rock drills, chisels, hammers, etc. Some steels are very hard, and may have their toughness increased by the addition of a little tungsten. According to Chernoff, tungsten steel after a few heatings becomes oxidised, and loses its distinctive properties. The St. Chamond Company in France have used tungsten steel for springs, it being claimed that the metal possesses one-third more carrying power than the best carbon steel. Tungsten steel in England is known as Mushet's special steel. It possesses a natural hardness of its own, and when upwards of 3 per cent. of tungsten is present, instead of being hardened by sudden quenching like carbon steel, it is actually softened. Being difficult to forge, it is generally cast into the desired form and ground to the desired shape. A peculiarity of iron-tungsten alloys in the absence of carbon is, that they are not strengthened or increased in hardness by quenching. Mushet steel, as manufactured at Sheffield, contains 9 per cent. of tungsten, which gives a self-tempered steel of great durability. It is considered to be the best tool steel for machine work, and may be driven at a great speed. The steel has a very fine and crystalline structure, and is less affected by the atmosphere than ordinary carbon steels. Tungsten steel is specially adapted for standard gauges. Like chrome steel it can be forged at a red heat, even with as much as 10 per cent. of tungsten present.

Tungsten steel is largely used for making permanent

magnets, usually about 5 to 7 per cent. of tungsten being employed. It is considered to have the highest power of retaining its magnetism after being fully magnetised.

Steel and Copper.—Guettier [1] states that "the alloys of iron and copper are difficult to procure by direct fusion of the metals; that copper remains in a pulverulent state within the iron, has a tendency to become precipitated to the bottom of the fluid mass, or in the moulds, and the combination is generally incomplete. Copper imparts to cast-iron a greyish lustre, probably due to uncombined copper."

Copper was formerly considered very injurious in iron and steel, even when present in minute quantity, but the late Mr. Willis of Landore stated that ·1 per cent. of copper produced no appreciable effect on the quality of steel. The injurious effects attributed to copper are very marked when sulphur is present in notable quantity, making the metal red-short. M. Choubly of the Firminy Steel Works has experimented on phosphoric steel containing copper, and he states that a sample of metal containing 0·5 per cent. of carbon, 0·15 phosphorus, 0·04 sulphur, and 1 copper rolled perfectly well.

Messrs. Ball and Wingham [2] have investigated the influence of copper on the tensile strength of iron and steel. An alloy containing:

Copper, - - - - - -	7·550
Carbon, - - - - - -	2·720
Manganese, - - - - - -	0·290
Silicon, - - - - - -	0·036
Phosphorus, - - - - -	0·130
Sulphur, - - - - - -	0·190

was bright, white in colour, crystalline, and very hard, but did not offer any great resistance to impact. Varying quan-

[1] *Guide Pratique des Alliages*, 1865.

[2] *Iron and Steel Institute*, No. 1, 1889.

tities of the alloy were melted down with Bessemer steel, and test pieces 1 inch by $\frac{1}{4}$ inch by $\frac{3}{16}$ inch were annealed before being tested. The following table shows the results:

No.	Copper.	Carbon.	Tensile Strength.
1	0·847	0·102	18·3
2	2·124	0·217	36·6
3	3·630	0·380	47·6
4	7·171	0·712	56·0

From these experiments it is clear that copper increases the tensile strength of iron. The simultaneous presence of carbon tends to prevent the more intimate association of copper with iron. In test piece No. 1 the fractured surface was somewhat fibrous, while No. 2 and the others were highly crystalline. Even in the absence of carbon copper makes iron extremely hard. Mr. F. Stubbs states that the presence of $\frac{1}{2}$ per cent. of copper in steel gives to it the property of preventing the oxidation of the steel on being subjected to a burning heat.

Mr. Stead[1] has investigated the nature of alloys of copper and iron, and states that these metals alloy together in all proportions by direct fusion, and in none of the alloys is there any tendency to separate into two conjugate liquid layers. He classifies the alloys into three sections:

A.—Alloys with traces up to 2·73 per cent. of iron.

B.—Alloys with between 2·73 and 92 per cent of iron.

C.—Alloys containing 8 per cent. and mere traces of copper.

All these are true alloys, being free from globules and knots of iron. The presence of carbon interferes with the union of copper and iron in proportion to the amount of

[1] *Jour. Iron and Steel Inst.*, No. 2, 1901.

carbon present. The amount of copper in grey haematite pig iron cannot exceed 7·5 per cent., and not more than 15 per cent. in steel, with 1 per cent. of carbon. In most carbon-iron-copper alloys, the amount retained in solid solution is not more than 7 per cent., varying with the rate of solidifying. Copper in cast iron does not appear to have any influence in retaining the carbon in the combined form, or in causing it to separate as graphite. Copper therefore in foundry iron need not be feared, as its only effect appears to be to raise the tenacity.

Copper in steel rails in small quantity does not materially affect the mechanical properties, but in steels, in which high ductility is required, especially in those with high carbon, copper is objectionable. Steel with copper, say up to 1 per cent., appears to resist corrosion better than the same steel without copper.

Steel and Molybdenum.—Dr. Thompson considers that of all the metals, molybdenum is the one with which iron unites most readily. With equal parts of the two metals the alloy is fusible with the blowpipe. With 1 part iron and 2 parts molybdenum, an alloy of a clear greyish-white colour is obtained. An alloy of 20 per cent. molybdenum is whiter than iron, very hard, brittle, tenacious, and has a granular fracture. Berthier considers the alloys of molybdenum and iron to be in every respect the analogues of those of tungsten and iron. They are generally greyish-white, hard, brittle, fine-grained, and magnetic. When the molybdenum is below 50 per cent. the alloys are somewhat fusible. Copper blast-furnace *bears* (as the metallic masses found in the hearths of old copper blast-furnaces are termed) chiefly consist of iron and molybdenum. [1] The influence of molybdenum on the properties of steel is supposed to resemble that of tungsten. W. V. Lipin compared two

[1] *Jour. Iron and Steel Inst.*, No. 2, 1897.

blocks of crucible steel, one containing 3·72 per cent. of molybdenum, 0·55 carbon, 0·1 silicon, 0·13 manganese, and 0·024 phosphorus, and another containing 3·82 per cent. tungsten, 0·55 carbon, 0·07 silicon, and 0·13 manganese. The metal did not rise on pouring, the slag of the molybdenum steel was half vitreous, greenish-grey, and showed a play of colours. The molybdenum steel gave a perfectly smooth surface, while the tungsten steel showed minute cracks, and was harder than the former. Heating to a very high temperature, such as is good for carbon and chrome steels, is unsuitable for molybdenum steel, and hardening in oil and subsequent annealing are almost useless for it. Energetic water hardening has more influence on molybdenum steel than on tungsten steel.

Ternary Alloys of Iron with Molybdenum, Chromium, and Tungsten.—De Beuneville[1] has conducted experiments to ascertain in what order of chemical affinity the above metals stand to iron. The alloys were made by melting these elements in pairs with iron, forming tungsten-chromium iron, molybdenum-chromium iron, and molybdenum-tungsten iron, the proportions being based on the atomic weights. They were first given as 1 : 1 in the iron, then as 5 : 1, and as 1 : 5. In the tungsten-chromium irons there is a conclusive indication that the iron by preference alloys itself with the chromium. Even when the preponderance of tungsten over chromium is as great as 5 atoms to 1, or 19 grms. to 1, the iron exercises a selective choice in favour of the chromium. In the molybdenum-chromium irons, the chromium is again by preference taken up by the iron. The probable reason for these results is considered to be the more ready dissociation of the chromium molecule. There appears from these results to be very little difference between molybdenum and tungsten as regards their combina-

[1] *Jour. Iron and Steel Inst.*, No. 1, 1895.

tion with iron, taking them in reference to chromium. In the molybdenum-tungsten irons there is a slight difference in favour of molybdenum. A large number of the results of a chemical examination of the residues, obtained after the action of different reagents on the alloys, point to a varied structure in the alloys. There appears to exist side by side a number of compounds, some readily attacked by reagents, and others inert, distributed with considerable uniformity throughout the mass. The compounds formed are not all ternary compounds. A small percentage of iron, in several cases accompanying large percentages of molybdenum or tungsten, show that these elements are present, in part at least, in some form other than that of ternary alloys. The form in which carbon exists in these alloys shows their heterogeneity. In one example, carbon was present in at least three forms, all being combined carbon: (1) Carbon evolved as ill-smelling hydrocarbons by the action of dilute acids; (2) carbon present in the residues obtained by acting on the alloys with bromine, which residues are not attacked by dilute hydrochloric acid; and (3) carbon found in the prismatic crystals. In these ternary alloys also is found the more complex carbides of chromium with iron and molybdenum, or tungsten. The hardness of these alloys cannot be attributed simply to change of carbon from the graphitic to the combined form, but to the formation of definite carbides.

Iron and Oxygen.—There are three well-known oxides of iron, all of metallurgical importance: ferrous oxide FeO, ferric or red oxide Fe_2O_3, and magnetic or black oxide Fe_3O_4. Ferrous oxide is unstable, rapidly oxidises in contact with air or other oxidising body, and readily unites with acids to form ferrous salts. This oxide is the principal base in all slags produced in refining iron, except in the basic process of steel making, where lime largely takes its

place. In combination with carbon dioxide it forms that most important class of ores termed spathic. Ferric oxide occurs in nature as haematite, and in the hydrated state as brown haematite. It is a stable compound, but at a white heat it gives up oxygen, forming the black oxide. The black oxide is very abundant in nature, forming the richest ore of iron. It is produced when iron is strongly heated in air or oxygen, and also by heating iron in contact with superheated steam. It may be looked upon as a compound of FeO and Fe_2O_3, in which the former is the basic and the latter the acid portion.

Iron is capable of absorbing oxygen when strongly heated in contact with air. Deville and Troost, by their classical experiments, found that oxygen and other gases could pass through metals. They imagined a new kind of porosity, more minute than that of earthenware, an intermolecular porosity due entirely to dilatation. Graham[1] has shown that when gas penetrates the substance of a metal, there is a previous absorption and possibly liquefaction of the gas. Since his time it has been abundantly proved that the presence in it of an element which is capable of appearing with the elastic tension of a gas must materially affect the mechanical properties of a metal. The occlusion of gases by metals is well known, and the importance of this action on iron, especially in regard to oxygen, is now claiming the attention of metallurgists. The absorption and retention of oxygen at the conclusion of the Bessemer blow is a powerful factor that has to be reckoned with, owing to its intimate association with the iron and its profound influence on the properties. The precise manner in which it exists, whether as a dissolved gas or an oxide, is not yet ascertained, though Müller has given strong

[1] *Proc. Roy. Soc.* vol. 16, p. 212; also *Trans. Roy. Soc.*, 1886, p. 399.

evidence in support of the view that the gas is dissolved in the iron. At any rate oxygen may be readily removed from iron by means of manganese and other deoxidisers. Carbonic oxide is another gas readily absorbed by iron, and its decomposition and recomposition are supposed to play an important part in the process of cementation. Silicon and manganese appear to be able to keep carbonic oxide in solution in iron.

The quantity of oxygen retained by iron is probably small, but this small quantity is very powerful in affecting its physical properties. The quantity seldom exceeds 1 per cent., and is often very much less. Probably the proportion retained varies with the temperature employed. Of course if manganese or any other deoxidiser is present the oxygen is greatly reduced, and may be wholly eliminated. Assuming that the oxygen is present as oxides of iron, the manganese may reduce such compounds according to the following equations:

$$Mn + FeO = MnO + Fe. \quad Mn + Fe_3O_4 = 3FeO + MnO.$$

The protoxides will then unite with silica, or phosphoric acid, as in the basic process. Oxide of iron is also reduced by silicon at high temperatures, thus:

$$3FeO + Si = 2Fe + FeOSiO_2.$$

It has been observed that, after rebuilding some open-hearth furnaces, the steel was frequently burnt, and as a rule 10 per cent. more air is used than is necessary to ensure the complete combustion of the gas. This excess of air is prejudicial to the iron from the point of view of oxygen. Ledebur considers that the maximum amount of oxygen that can be dissolved in steel is 0·29 per cent., which is equivalent to 1·3 per cent. of ferrous oxide. Further, that more than 0·1 per cent. of oxygen is not contained in steel that will roll well. The specific gravity of

steel is inversely proportional to the quantity of dissolved oxygen. Romanoff[1] states that steel that will roll well with 0·1 per cent. of oxygen in it has a minimum specific gravity of 7·9, and with 0·2 per cent. the specific gravity falls to nearly 7·8. An increase of oxygen from 0·15 to 0·3 per cent. causes the resistance to increase from 11·09 to 11·28 in wire for telegraphic purposes, and the specific gravity falls to 7·72. Ledebur[2] states that manganous oxide is not quite insoluble in iron, and that part at least remains dissolved in steel if the metal is cast immediately after the addition of ferro-manganese.

Iron and Hydrogen.—This element is usually present in iron although the quantity does not often exceed 0·01 per cent. by weight. It is present as gas, both in the free state and in ammonia. It may also exist as a compound in the solid state, but the affinities must be feeble, as the element is easily expelled. It escapes from iron when drilled under a liquid, or when heated in vacuo, and when liquid iron is solidifying from fusion. In the latter case it is accompanied by nitrogen and carbonic oxide. It is often the cause of blowholes.

Müller and Stead have shown that hydrogen is evolved from steel when the latter is drilled. Roberts-Austen has shown that a critical point occurs in cooling electrolytic iron, due to the escape of hydrogen, and this indicates that some combination of hydrogen and iron exists At 7° C. a considerable quantity of hydrogen is evolved. In fact in gradually cooling from a high temperature in vacuo, hydrogen is evolved the whole time, but chiefly above 1300° C. Heyn has shown that if ingot iron is heated in hydrogen between 730° and 1000° C., and then suddenly quenched, the metal is much harder than it is when heated in air and

[1] *Stahl und Eisen*, vol. 19, p. 265.
[2] *Stahl und Eisen*, vol. 19, p. 269.

then suddenly cooled. Care should therefore be taken not to heat iron for bending tests in contact with unburnt gas. Iron rendered brittle in this way may be restored if annealed in air. Iron low in carbon only requires to be annealed at 250 to make it soft, but high carbon steels require a higher temperature.

CHAPTER XVIII.

METHODS OF PRODUCING STEEL.

THE different methods of making steel may be classified thus: (1) By direct methods, as in the Catalan forge, etc.; (2) from pig iron in the finery; (3) by puddling pig iron; (4) by the cementation process; (5) by the treatment of blister-steel, or iron and carbon in crucibles; (6) by a pneumatic process, such as that of Bessemer; (7) in an open-hearth, such as that of Siemens.

1. **The direct methods** in the Catalan forge, Siemens rotator, Blair's furnace, etc., have been described when treating of iron.

2. **Finery method.**—This differs but little from that employed in making iron, the operation being conducted so as to leave sufficient carbon in the bloom to constitute steel. This is done by prolonging the operation, thus leaving the iron a longer time in contact with incandescent carbon, and by using a less oxidising blast. The best pig irons for this purpose are the strongly-mottled and manganese varieties. This method is now almost obsolete.

3. **Puddling method.**—This is essentially the same as that used for wrought iron, but greater care is required in selecting the pig iron employed, which should preferably contain manganese. This metal acts in retarding the decar-

burisation, in consequence of its superior affinity for oxygen, by constantly reducing tetroxide of iron to protoxide, and the protoxide to metallic iron, thus retarding the carbon from being oxidised. Oxide of manganese also produces a very fluid slag, which covers the metal more effectually and is easily expelled. The presence of a little metallic manganese improves the quality of steel. The addition of spiegel-eisen to the charge of non-manganiferous pig iron does not answer so well as when the manganese already exists in the pig iron employed.

A thinly liquid slag protects the iron from a too rapid oxidation, and thus permits a more prolonged rabbling, so as to remove the impurities other than carbon. A slag with a double base of FeO and MnO, containing about 10 per cent. of the latter is very fusible, and but feebly decarburising. Only one class of iron is operated upon at a time, as in a charge of mixed irons one kind would be purified sooner than another.

The melting of the charge must be rapidly performed in order to lessen oxidation. The rabbling requires great care, and when the metal "comes to nature" in the form of fine white, brilliant grains, it indicates good and uniform steel. A lower temperature is employed during the final stages of the rabbling period than when puddling for iron, so that the metal separates more readily while carbon is still present in it. The balling is done in a neutral atmosphere, and the balls taken quickly to the hammer. Eight to nine charges of iron would be worked off in the same time as six to seven of steel.

CHAPTER XIX.

CEMENTATION.

CEMENTATION is the name given to the process whereby two solid bodies, one of which is a powder, react on each other, without fusion, so as to alter the nature and properties of at least one of them. The powdered body that produces the required change is termed the cement, and the body acted upon is said to be cemented, or to have undergone the process of cementation. One of the methods of making steel is by cementation, in which bars of malleable iron are embedded in charcoal, and exposed to a high and prolonged temperature, in a closed vessel, from which air is excluded, for a considerable period, or until a portion of the carbon has become so incorporated with the iron as to completely alter its composition, structure, and properties. In fact, the fibrous bar iron has been changed into a heterogeneous crystalline mass, the surface of which contains numerous blisters, hence the name "blister steel."

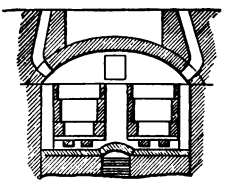


FIG. 90.

The furnace employed is represented in transverse section in Fig. 90. It consists of an oblong rectangular chamber, divided into two parts by a long, narrow fireplace, which

passes through the centre, and is provided with a door at either extremity, through which fuel is supplied. On each side of this is a chest, or converting pot, made of fire-brick or fire-stone, and so supported on flues as to allow of the heat and flame circulating round them, before escaping to the chimneys. An arched roof is thrown over these pots and the fireplace by which they are heated. Manholes are left in the brickwork at the ends, for the purpose of introducing the iron bars into the furnace. The pots vary in size, an average one measuring 15 feet long by 3 feet square. Smaller chests are also employed, and are said to produce steel of more uniform quality. The depth of the fireplace varies with the nature of the fuel and the size of the chests to be heated; the space between these is usually about 18 inches. In some cases only one chest is employed. It is then placed across the fireplace. The degree of heat applied is regulated by opening or closing apertures in the arch, and by limiting the supply of air to the grate.

To charge the chests, a layer of coarsely-powdered charcoal is placed on the bottom, then a layer of iron bars, placed side by side, as many as the width will allow without touching each other. These alternate layers are continued until the chests are full, which contain about thirty of these layers of charcoal and iron. The top is covered with a thick layer of charcoal. Finally, the surface is covered with a layer of "wheelswarf," obtained from the troughs of grindstones, consisting of siliceous matter and particles of iron intermixed.

The bars of iron used are about 3 inches wide and $\frac{3}{4}$ inch thick, laid flatways on the bed of charcoal. The charcoal used is first made to pass through a riddle of about $\frac{1}{2}$ inch mesh. One of these chests would hold about 13 tons of iron. The average quantity of charcoal per heat is about 200 bushels, and the amount of coal burned in the grate may be

15 tons. The charging having been completed and the covering of wheelswarf put on, the manholes are bricked up and the fire lighted, care being taken to keep up a temperature of glowing redness, during periods, varying with the nature of the steel required. The effect of heat is to fuse the wheelswarf, which then forms an air-tight covering and prevents any access of air to the bars of iron. For mild heats the furnace is fired for about eight days; for medium heats about ten days, and for hard heats about eleven days. The progress of the operation is ascertained by means of "trial" bars, which are removed through holes left in the ends of the chests, and from an inspection of the fracture of these when cold, the degree of carburisation is judged. The ends of these trial bars protrude from the ends of the furnace, but air is prevented from gaining access by luting them round with clay. After firing, the furnace is banked up, and the chests with their contents are allowed to cool down during a period of about fourteen days. For the first part of this cooling-down period the temperature is sufficiently high to continue the cementation, because the whole mass has to cool down from an initial period of about 1000° C., so that it remains for some time at a red heat.

As soon as the temperature has fallen sufficiently low for a man to enter, the bars are removed, broken, and assorted according to the quality, as determined by the appearance of the fractured surfaces. The iron employed for cementation in this country is either English or Swedish, the latter, being of very high quality and practically free from phosphorus, is the most esteemed for making the higher qualities of steel, and hammered bars were formerly preferred to rolled bars. The variety termed "spring" steel is of the lowest degree of carburisation, and the best cast-steel is made from that which has been most perfectly converted. The steel bars, as removed from the converting

furnace, are in that state that procures for them the name of "blister" steel. It may be treated in two different ways, according to the purposes for which it is required. By reheating and drawing, or by fagoting and welding or rolling, it may be made sufficiently malleable for ordinary work. The mild blister steel is used for springs, and the higher carbon steel after fagoting and welding is termed "shear" steel, or single shear steel. By cutting up the bars of single shear steel, fagoting, and re-welding, the variety known as double "shear" steel is produced. The surfaces of the bars are covered with clay and borax wash during the reheating, to prevent any of the carbon burning off.

Cemented bars are classified into six grades, viz., 2, 3, 4, 5, 6, and a special kind, termed "glazed" bar, or doubly converted bar. Formerly No. 1 was also made, but this mild variety has been superseded by Bessemer and open-hearth steel. Mild cemented bars are distinguished by the central core of unaltered iron, while the more highly cemented bars show large crystals when fractured ("flaked"), which Arnold attributes to the fracture occurring along the junctions of the cementite walls, enveloping the crystalline grains of pearlite.

Much diversity of opinion has been expressed as to the cause of the blisters on the surface of cemented bars, which are probably due to gaseous expansion from within while the iron is in a highly heated state. They are generally attributed to the action of the cementing material on the slag, which is a ferrous silicate, the oxide of iron of which is reduced, with the formation of carbonic oxide, which, on attempting to escape, raises the surface of the metal into blisters. These blisters are of varying size, sometimes several inches long, but generally from $\frac{1}{4}$ inch to an inch in diameter. If the iron has been previously fused and freed from slag before being submitted to the cementing

process, no blisters appear on the surface. On careful inspection of the interior of the blisters under the microscope, Mr. T. W. Hogg[1] found globules of slag or glassy-matter and he attributes the appearance to the presence of slag and reduced iron. On cutting out several of the blisters and analysing the interposed slag, he found 0·6 to 1·3 per cent. of carbon, 0·2 to 0·1 of interposed slag, and 0·015 per cent. of silicon. Notwithstanding all the investigations made as to the cause of the blisters, there is still no proof that the slag is decomposed by the carbon, and it is more likely, as suggested by Louis, that carbonic oxide is formed by the decomposition of the magnetic oxide of iron always present in iron slags containing much iron. Moreover, the exact composition of the gas enclosed in the blisters has not yet been accurately determined.

. If air has gained access to the bars during conversion they are rough on the surface and have a skin of iron, due to the oxidation of carbon, and are termed "aired bars." When a bar has been submitted a second time to the cementation process, it is termed "glazed" bar.

The manner in which carbon is passed into the iron in cementation is not exactly known. It may be transmitted in the form of gaseous compounds of carbon, such as carbonic oxide, cyanogen, and hydrocarbons such as marsh gas. According to this view the gases are decomposed in the pores of the bars, the carbon uniting with the iron. Thus carbonic oxide gives up carbon, being changed to carbon dioxide. Cyanogen and hydrocarbons also yield up their carbon to the iron, and the nascent nitrogen and hydrogen again unite with the surrounding carbon which restores them to their original condition. Likewise the carbon dioxide cannot exist as such in the presence of carbon, and is therefore reduced to carbonic oxide again.

[1] *Jour. Soc. Chem. Indus.*, p. 323, 1896.

These gases may act as carriers of carbon towards the interior of the iron. On the other hand, it may be that the gaseous compounds of carbon are decomposed at the surface of the bars, and the combined carbon transmitted to the interior by the iron itself. It is well known that charcoal has the power of occluding much gas, and the quantity of charcoal present in the converting chest must originally contain a considerable quantity of air, so that the oxygen, and probably the nitrogen, are in a condition readily to unite with carbon at the high and prolonged temperature existing in the furnace. In the blast furnace, iron at certain temperatures decomposes carbonic oxide, with the deposition of carbon. In the same way, in the converting chest, carbon would be deposited in the pores of the iron bar, and thus unite with the iron at a temperature much below the melting-point of iron. As mentioned when dealing with the subject of carbon in iron, Arnold considers that the diffusion of carbon into iron is effected by the carbide of iron Fe_3C, and the sub-carbide $Fe_{24}C$, that the latter is more rapid in its action, and acts at lower temperatures than the former. Hence it should be possible to convert iron into steel up to the saturation point (0·9 per cent. carbon) at about 800° C., but that it is not possible to produce supersaturated high carbon steel unless a temperature of 950° is reached and maintained, as in practice. Roberts-Austen considers that the passage of carbon into iron is a case of true diffusion, although there is dissociation by the diffusion.

Case Hardening.—This is a process of partial cementation, in which a casing of steel, of varying degrees of thickness, is imparted to iron goods according to the depth of conversion required. The advantage of this is its cheapness, and at the same time one may get a hard exterior and a soft, pliable interior. For this purpose

charcoal, carbonaceous matter such as burnt leather, and cyanide compounds such as ferrocyanide of potassium, are used as the carburisers. An iron box is used in which the iron articles are packed with animal charcoal. This is covered up, and the whole heated for varying periods, in a muffle furnace, according to the degree of carburisation required. The conversion may extend to a depth of $\frac{1}{4}$ inch in four hours. The work is hardened by plunging into water while red hot. Small articles are case hardened by rubbing them while hot in powdered potassium ferrocyanide, reheating to decompose the powder, and then plunging them in water.

Harveyised Steel Plates.—In this process an armour plate, consisting originally of very mild steel, is cemented in such a manner as to produce a face of very hard steel, the steel becoming gradually less hard from the face to the unaltered soft back. Such a plate of mild steel, containing from 0·10 to 0·35 per cent. of carbon, is placed upon a bed of finely powdered dry clay or sand, deposited upon the bottom of a fire-brick compartment erected within the heating chamber of a suitable furnace. The compartment is then partially filled up with granular carbonaceous material, which, having been rammed down upon the plate, is in turn covered with a stratum of sand, and upon this there is laid a covering of heavy fire-bricks. The furnace is raised to an intense heat, which is kept up for such a period of time as may be required for the absorption, by the layer of metal below the upper surface of the plate, of an additional 1 per cent. of carbon. The temperature of the heating chamber outside the treating compartment is raised to about that required to melt cast iron, and is kept up for a greater or less length of time, according to the depth of the stratum of steel which it is intended to charge with an excess of carbon.

The following is an example of this process: A plate 10½ inches in thickness, composed of a steel containing 0·35 per cent. of carbon, may be charged with additional quantities of carbon, gradually varying in amount from about 0·10 per cent. at a depth of 3 inches beneath the surface of the exposed sides of the plate, to 1 per cent. at the surface, by a continuance of the treatment for a period of 120 hours after the furnace has been raised to the required temperature. The depth to which this increased degree of carburisation can be allowed to penetrate increases with the thickness of the plate. This penetration is dependent not only on the temperature of the furnace and on the length of time the plate is exposed to the cementation process, but it is also greatly facilitated by the continuous firm compression of the carbonaceous matter against the plate. The plate, when sufficiently carburised, is freed from its carbonaceous covering, allowed to cool to a cherry-red heat, and then hardened. In this connection it is interesting to note that such plates hardened by a spray jet gave unequal results on trial, the upper corners showing resistance to penetration by shot, while the bottom of the plate was penetrated. This was due to the heated water from the cooling of the upper portion of the plate acting as a protective coating to the lower portion and thus preventing rapid cooling.[1]

Fig. 91[2] shows one of the furnaces with the front removed, as used at Messrs. Vickers & Sons. The furnace, it will be seen, is of the car type, the top of the car being covered with several thicknesses of fire-brick to protect it from the heat of the furnace. On these a series of flues is constructed, extending the full length of the car, for the passage of the hot gases. The armour-plate is laid on the

[1] *Iron Age*, Vol. 48, p. 736.

[2] *Engineering*, Nov. 12th, 1897.

brickwork forming these flues. Walls are built on all four sides. The face of the plate is covered with powdered charcoal, and on this is placed another plate face downwards, so that two are carburised simultaneously. Over and around all is a covering of ordinary sand. The car, thus loaded with the assistance of a pair of 50-ton hydraulic sheerlegs erected for the purpose, is run into the furnace and the front door closed and made airtight. The hot gas

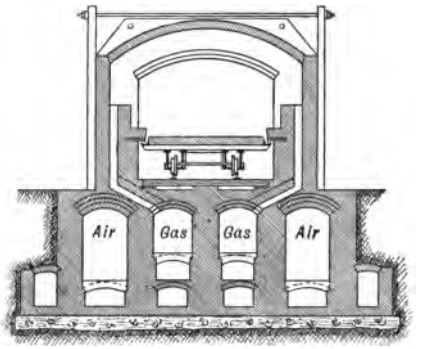


FIG. 91.—CEMENTATION FURNACE FOR ARMOUR PLATES.

enters at the back, the flames pass over the top, down at the front, through the flues underneath the plates, thence through exits which butt against the flues on the car, and thus to the chimney. The plates, it will be understood, are completely within an oven formed of bricks and sand, and the charcoal can only be heated through the flues in the brickwork or through the sand and metal, so that the plates absorb the carbon from the charcoal. The process occupies about a fortnight. The newer furnaces are gas-fired, the producers being of the type described in connection with steel melting. With the gas-fired furnace the heat can be more accurately controlled, giving not only a more uniform result, but a higher

economy. The furnaces are 21 feet wide and 36 feet long, so that they may take exceptionally large plates. The outer walls of the furnaces are of brickwork, cased round with rolled-steel plates, supported by rolled joists, and braced together by steel bolts. Beneath the furnace are four regenerative chambers for gas and air supply; the valves for gas and air supply are of the mushroom type, and fitted to the pipes where they communicate with the regenerator chambers and with the chimney flues. The car is built up of rolled H beams, the top being covered with 9 inches of fire-brick work, while the sides of the car are fitted with channel-irons filled with sand. Into this channel, plates built on the side walls of the furnace engage, so as to prevent leakage of cold air into the furnace. The car is supported on ten wheels, the axles being fitted with roller bearings. The wheels are below the furnace-bottom and not subjected to heat. The cars are hauled in and out by several means—an endless chain driven by a steam engine and spur gearing, while in other cases the endless chain is driven through gearing and by rope, or by electric motor or locomotive. To facilitate working, doors, made of cast iron filled in with fire-brick, are now built in nearly all the furnaces, and when the car with its load of armour plate and charcoal is run in, these are lowered or lifted by gear, consisting of two chains passing over guide sheaves.

The cemented plates after removal from the furnace are machined, and the necessary bending done before they are hardened. Reheating is always necessary, and a special movable car furnace is provided for this purpose. The quenching for hardening is done by means of water sprays playing on to the red-hot plates.

C. W. Bildt[1] observes that the cementation process for producing finished wares is characterised by the fact that

[1] *Jernkonterets Annaler*, Vol. 56, p. 242.

it takes place at a temperature below the melting point of the embedded substance, and that the cementation powder consists of a mixture of 60 per cent. of charcoal powder, and 40 per cent. of bone meal. By the addition of the latter the cement powder remains compact on "burning," thus keeping out the air better, and causing the absorption of carbon to be more regular. Weld iron or good ingot iron low in carbon is employed. Either the whole surface of the article may be cemented or only portions of it, and the cemented substance is then a finished product and is not remelted. When only a portion of the surface is to be subjected to cementation the remainder is covered with clay or some other fire-resisting materials. The cementation furnace, with its fixed cementation box and its removable hood, is cooled down after each heat for the removal of the product, and for charging fresh material. The method may be made continuous by using a fixed hood and placing the box on a trolly. One box is then immediately replaced by another. This has given much satisfaction in practice, as, too, have other arrangements. It is, however, always necessary for the box to be heated evenly all round, and for this purpose gas firing is very well adapted. The box itself and the inner parts of the oven are of fire-resisting material. The materials to be treated are placed 2 or 3 inches from each other, and from the walls, according to their size and the desired depth of the carburised layer. The cementation powder is not packed in tightly, but is placed loosely around the iron materials. If these fall at all during the operation the powder then follows them. The filled box is protected by a coating of clay to a depth of a few inches. A firing lasts from twenty-four hours to several days, according to the size of the box, in order to attain a temperature within it of 900° or 1000° C. This temperature is measured by means of a tube built into the

chest. In this way articles may be cemented which vary in size from the smallest possible up to that of armour plates. From 1·0 to 1·2 per cent. of carbon is taken up on the outside, and the following shows the way this varies in depth from the surface inwards:

Depth in inches,	0·00	0·50	1·00	1·25	1·50	1·75
Carbon per cent.,	1·00	0·70	0·40	0·27	0·25	0·25

The above refers to 18-inch armour plate of open-hearth steel, with an initial 0·25 per cent. of carbon, which was cemented for a period of twelve days, counting from the time when the right temperature was reached up to the removal of the flame. A long continued heat and a high temperature render the metal coarsely crystalline and brittle. It had subsequently to be subjected to much mechanical treatment to make it a useful material, either by rolling or hammering hot or cold. This does not affect the relation between the cemented and uncemented material, except as far as change in shape is concerned. Suitable and unsuitable metals with their chemical compositions are shown below. Nos. I. and II. are well suited for the cementation process, No. IV. less so, and No. III. not at all. This latter, it will be seen, is high in both phosphorus and sulphur.

	I. Per Cent.	II. Per Cent.	III. Per Cent.	IV. Per Cent.
Phosphorus,	0·030	0·020	0·120	0·034
Sulphur,	0·008	0·024	0·070	0·015
Silicon,	0·040	0·006	0·012	0·135
Manganese,	0·020	0·170	0·380	0·620
Carbon,	0·040	0·080	0·080	0·300

CHAPTER XX.

CRUCIBLE STEEL.

THE introduction of the high class material known as best cast steel is due to Benjamin Huntsman, who was born in 1704 and made his historical casts of steel about 40 years later. It seems that at that time the blister steel was imported from Germany or Sweden, or a raw puddled bar had to be used. Huntsman had first to find a sufficiently refractory material for making his crucibles, as at that time very little was known of the chemical constitution of fire-clays, and it was also difficult to get the necessary fuel for his furnaces.

The bars of blister steel are broken up small and melted in crucibles in ordinary wind furnaces. Each crucible holds about 56 lbs. of steel for the first heat, 50 lbs. for the second heat, and 45 for the third heat. The reason for this diminution in quantity in successive heats in the same crucible is, that the slag that forms on the top of the metal corrodes and cuts the crucible, and if the second charge of metal were the same in quantity as the first, the slag would corrode the crucible further in the same place and render it too weak to support the weight when lifted up for teeming.

The same remarks apply to the third heat. The contents

of the crucible are poured into cast iron or steel moulds. Where large masses of steel are required, the contents of a great number of crucibles may be poured into a foundry ladle, and the casting made from the ladle. Or, as in the old Krupp method, the casting may be done by the men bringing up a constant succession of pots, so that the metal may run into the mould in a continuous stream from the crucibles, each of which contains about 70 lbs. of steel.

The ordinary furnace or teeming hole (Fig. 92) is a rectangular cavity, 18 to 24 inches square, and 3 to 4 feet in depth. It is lined with refractory material. A number of these are arranged along one side, or two rows may be built back to back. The teeming holes are on a level with the shop floor, and covered with iron plates while the metal is melting. The melting chambers are only separated from each other by a brick wall, with the exception of the refractory lining, which, in Sheffield, is ganister. This is rammed in round a wooden core or template, elliptical in shape, 26 inches long by 19 inches wide. When this is withdrawn the space thus lined is an elliptical cavity, capable of holding two pots. The ends of the fire-bars rest on bearers, built in the brickwork below the level of the roof of the vault beneath. This enables the bars to be accessible for withdrawal in case of a pot breaking. Each fire has its own ashpit, as well as its own flue. These flues

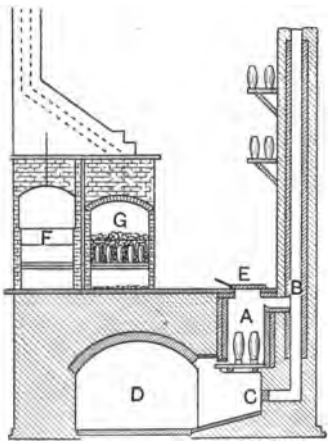


FIG. 92.

are carried up in groups of five or six into a stack about 40 feet high, and each one is continued down to the ashpit below. By inserting a brick into this opening, and into the flue, the draught of each fire can be regulated. Around the sides of an old-fashioned melting house are shelves for drying the crucibles previous to annealing. They are now generally dried in special chambers erected for the purpose. The annealing is done in annealing ovens which are rectangular chambers of brickwork, having sliding doors at the front, and a small flue carries away the products of combustion of the fuel. Upon the bars a layer of live coals is first placed, and then some coke. The crucibles are placed upside down on the fire, and the space between and above is covered up with coke and coal. The slow combustion of the fuel enables the pots to be gradually heated to a red heat, and then they are allowed to cool down slowly.

Steel-melting crucibles are made of a mixture of different fire-clays, burnt clay, and a little coke dust. In Sheffield it is a common practice to use a mixture of Burton and Stannington clays, to which Stourbridge clay is sometimes added. If the pots are required to withstand excessive heat, china clay is also added. The raw clay forms about two-thirds and is mixed with one-third of old pots and coke dust, the whole being ground very fine and carefully sifted. The pots are made in an iron frame, using a wooden plug for the inside shape. In hand-made crucibles there is a hole left in the bottom of each pot, which, when placed in the furnace rests on a fireclay stand, which rests on the firebars. The workman, before charging in the steel, throws a handful of sand into each pot to fill up the hole; the heat of the fire causes this to frit and close up the hole, as well as to cement the bottom of the crucible to the stand, which is removed along with the crucible when the latter is lifted

from the fire for teeming. In machine-made pots there is no hole in the bottom, because no centring pin is required in order to make the thickness uniform.

Graphite or plumbago crucibles are also used for steel melting. They last longer than clay ones, endure rougher usage, and for the same size can carry a larger quantity of metal. The loss of steel is also less, but much more liable to contain carbon and silicon obtained from the crucible walls. All steel-melting crucibles are provided with a well-fitting cover, sometimes with a hole in the centre through which a rod can be passed for examining the charge. This hole is fitted with a fire-clay plug during the melting time. Graphite crucibles are chiefly used in America, and made so as to be capable of holding 60 to 90 lbs. each. Larger ones are also used for heavier charges. The average life of such crucibles is from 4 to 6 heats, as compared with 3 heats in a clay pot. The life of a pot also depends on the kind of steel melted in it, being longer for hard than for mild tempers. Like clay pots they become corroded at the slag line, hence the weight of charge is generally diminished at each successive charge, say 80, 78, 75, 72, etc. In some works the pot is filled at each heat, irrespective of the slag action.

A weighed ball of clay and graphite is taken for making each crucible, and placed in a plaster-of-paris or wooden mould, having the external shape of the crucible, centred on a potter's wheel, and a cast-iron plug is driven into the clay to form the internal shape. After drying, the crucibles are baked in a pottery kiln, as in the case of ordinary crucibles. The air is excluded as much as possible to prevent burning out the graphite. This operation takes about a week. After baking, a drab-coloured surface is imparted to the graphite crucibles, due to the external burning out of the carbon. A graphite crucible will with-

stand great alterations of temperature without cracking, but at a steel-melting heat they are not considered so tough as clay pots, but the latter tend to crack and become brittle when cold.

A gas-fired crucible furnace was introduced by Siemens, the general arrangement of which is shown in Fig. 93. It is of the ordinary regenerative type, with two pairs of regenerators for heating the gas and air respectively. The

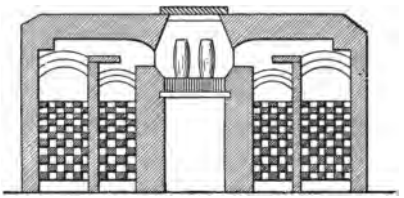


FIG. 93.

saving of fuel as compared with the old form of air furnace is as 4 to 5. That is, the gas furnace will burn 4 tons of coal as compared with 5 tons of coke in the air furnace. But it must be also remembered that the gas furnace burns common slack, so that the difference in cost of fuel is very considerable. The regenerative furnace may be constructed to hold any number of pots up to 30, a 24-pot furnace being a convenient size. The upper portions are built of silica bricks, and much expense may be saved by patching up the blocks between the ports with ganister, when defective, instead of waiting to put in new brickwork. A 24-pot furnace occupies a space of about 20 square feet and is placed entirely below the ground level. For ordinary qualities of steel 13 heats per crucible per week may be obtained. Good pots are required and the following mixture is recommended for a 60-lb. pot: Stannington clay 9 lbs., Burton clay 11 lbs., China clay 10 lbs., and coke dust 1 lb. The coke hastens the drying, strengthens

the pot when hot, and assists in killing by promoting the absorption of silicon. Each melting hole has a single opening for drawing and charging, and closed with movable covers, as in the ordinary teeming hole.

The Nobel liquid-fuel furnace is an arrangement for heating a number of crucibles with refined petroleum. It is cheaper to build than a gas-fired furnace, and uses less fuel than the solid-fired furnace, but the cost of fuel is greater when burning petroleum than when burning gas. Each furnace contains three holes, two of which contain two crucibles each, and the third space is left empty. These three holes are arranged in a row, so that the flame from the combustion chamber passes through them in succession, before going into the chimney.

Charging.—The charge of blister steel, after previous selection of the best portions of the converted bars, is introduced into the crucibles through a wrought iron funnel, termed a charger, which is held by one workman over the crucible while another workman tips in the metal from an iron pan. In America the graphite crucible is filled while cold, at any rate in the direct method of making steel from iron and charcoal, without previous conversion; the charge consisting of iron, charcoal, and a little oxide of manganese. In Sweden one plan is to add spiegel-eisen or ferro-manganese to the charge just before the metal melts. After a crucible is charged, the lid is put on, the fire made up with coke, and the top of the furnace closed. In about three-quarters of an hour the fire will want replenishing, and by the time this second fire has burnt down the steel will begin to melt, and the workman by introducing an iron rod into the metal can feel whether any unmelted lumps are left. Fuel is then added accordingly. The melting in an ordinary furnace takes four to five hours. Care must be taken that no coke falls into the crucible, because it will

make the steel red-short. The metal is then said to "stare," *i.e.* it has a brilliant appearance when fractured. A second heat is worked off in the same crucible in much less time, about 2½ hours.

When the workman judges that the steel is ready, he introduces a pair of "puller-out" tongs, which clip the bellied part of the crucible, and grip it with sufficient tightness to allow of it being pulled out without breaking the pot or allowing it to slip. The crucible having been placed on the floor of the melting house, is lifted to the mouth of the mould for teeming. The jaws of the "teeming" tongs form more than half a circle and in these jaws the belly of the crucible is clipped by the workman, who so pours the metal into the mould that it does not touch the sides. The teeming tongs for large crucibles consist of a barrow mounted on a central pivot, fixed to the axle of a pair of wheels, whereby the pot can be tilted for teeming and also run along the iron-plated floor.

Before lifting the crucible from the fire after the steel is melted, it is allowed to stand some time to "kill" the metal. If the metal were poured as soon as melted the casting would be full of blowholes, but by keeping it molten in the crucible for some time before pouring, the metal casts much sounder, forming a pipe at the top, instead of rising, as is the case with too hot metal. This is termed killing the steel. The effect is probably caused by the reduction of some of the silica in the crucible walls; the reduced silicon entering the steel increases the solvent power of the metal for gases, and thus prevents blowholes. When the metal is kept melted in a vessel from which no silicon can be reduced the metal is not killed by standing, and does not cast sound. If the killing is unduly prolonged the metal teems "dead," runs dull, is hard and brittle when cold, but it is free from blowholes.

This is probably due to the absorption of too much silicon. The softer the temper of steel the more it tends to rise in the mould after teeming, and therefore requires more killing than the harder tempers of steel. It is with the milder tempers that the greatest difficulties as regards unsoundness arise. "Dead-melting," proper killing, and careful teeming will tend to prevent blowholes being formed, and piping may be mitigated by teeming the metal slowly towards the end of the cast, so as to continue the flow of metal into the mould while solidification is taking place, and thus partially filling up the pipe. Steel that has not been properly killed will teem "fiery," throwing out sparks.

The moulds into which crucible steel is usually cast are made in two halves, which, when clamped together, form a cavity of the desired shape of the strip of metal to be cast therein. They are held together by rings and wedges, which can be readily knocked in to keep the parts tight, and just as easily knocked out again to release the cast strip of metal. Before putting the halves together they are well warmed and coated with a layer of charcoal and oil, in order to prevent the steel sticking to the mould. Sometimes a cream of fire-clay and water is used, or the two halves are held over a very smoky flame to deposit a layer of soot. After the moulds are so coated, or "reeked," as it is termed, they are fitted together and placed upright ready for the metal to be teemed in. The metal is first skimmed, to remove the floating slag, by means of an iron rod having a knob of slag at the end, and termed a "mop." The mop cools the slag, which then adheres to it, and by moving the mop over the surface, practically the whole of the slag adheres to it. The metal being now clear, the workman can judge of the proper temperature for teeming. After the crucible is emptied it is returned to the "puller-out" at the fires, who, after detaching any slag and clinker, puts it

back into the fire, ready for another charge. As the milder tempers of steel are apt to rise in the mould, the latter is covered with an iron stopper, and sand thrown on. Two to three tons of coke are required for melting one ton of steel.

Many modifications of the above method of making steel in crucibles have been introduced from time to time, but for the most part, as the iron used is of inferior quality, and impurities are also introduced by means of the "physic" added, the products are inferior to that of the best cast steel made from blister steel. An old method was to cut up bar iron or puddled bar into suitable pieces and introduce them into a crucible along with charcoal. When the iron was raised to the melting point, a small quantity of spiegel-eisen was added. If the milder qualities of steel were required the carbon was omitted, as the spiegel introduced the necessary amount. Plumbago pots were generally used. In some cases steel is made from iron and charcoal together with a little oxide of manganese.

The question may be asked, What is meant by good crucible steel? No tests exist by which it may be stated with certainty in what way crucible steel differs from steel made by other methods. Chemical and physical tests only enable conjectures to be made as to the origin of the steel. It is customary to speak of all ingot steel as cast steel, whatever its origin, and to call all steel suitable for the manufacture of tools, tool steel. It is, however, a common notion of consumers that crucible steel is superior to all other kinds, and of high quality. This may be accepted as very near the truth for the crucible steel made from the best charcoal iron, and converted by the cementation process previous to melting. But much steel is made in crucibles without previous cementation, and this is generally of inferior quality. A good quality cannot be made in crucibles from inferior iron, although good steel can be

made from common pig iron in the open-hearth process. Poor quality iron is often used in the crucible process when only a homogeneous and dense metal is required, usually in conjunction with certain definite tensile properties, and which is not required for tools of high quality. For steel castings crucible steel generally yields sounder metal than the open-hearth or the Bessemer process. This may be due to the small quantities operated upon in the crucible process and the greater command of the workman over the whole charge. As an example of the best kinds of crucible steel, the following analyses may be taken:

Carbon.	Silicon.	Manganese.	Phosphorus.	Sulphur.
1·31	0·05	0·14	0·010	0·003
1·44	0·10	0·14	0·015	—
0·96	0·10	0·13	0·012	—

It is difficult to make crucible steel of the above composition that is free from blowholes and oxides, so that manganese is generally added to the charge if the iron does not contain that element, with the result that the steel is sounder, but higher in manganese and silicon. Good cast steel ranges from 1·6 to 0·78 per cent. carbon, manganese from 0·5 to 0·23, silicon from 0·25 to 0·04, and phosphorus about 0·02 per cent.

The proportion of carbon contained in steel is designated its "temper," which has nothing to do with tempering. In the same way the higher carbon steels are termed "hard' steels, which has nothing to do with the process of hardening.

Seebohn gives the following list of useful tempers for steels:

Razor temper (1·5 per cent. carbon). Easily burnt by overheating.

Saw-file temper (1·35 per cent. carbon). Should not be heated above a cherry-red heat.

Tool temper (1·25 per cent. carbon). Useful for turning tools, drills, and planing-machine tools, cutters, etc. Can be welded.

Spindle temper (1·12 per cent. carbon). Useful for mill-picks, cutters, large taps, screwing dies, etc.

Chisel temper (1 per cent. carbon). Combines great toughness with power of being hardened at a low red heat. Can be welded, and adapted for tools where the unhardened part is required to bear the blow of a hammer without breaking, as in cold chisels, etc.

Set temper (0·9 per cent. carbon). For cold-sets to withstand heavy blows.

Die temper (0·75 per cent. carbon). Tools, which must be hard and yet withstand hammering, concussion, and great pressure.

A series of American crucible steels analysed by Blair is as follows :

No.	Total Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.	Copper.	Cobalt and Nickel.
1	0·973	0·213	0·003	0·025	0·073	0·008	0·008
2	0·886	0·196	0·002	0·037	0·185	0·006	0·039
3	0·694	0·128	—	0·057	0·137	0·010	0·023
4	0·994	0·140	0 003	0·027	0·101	0·006	0·039
5	0·401	0·085	0·006	0·032	0·112	0·008	0·047
6	0·904	0·061	—	0·026	0·108	0·004	0·034
7	0·915	0·191	0·002	0·034	0·086	0·002	0·031
8	0·238	0·105	0·012	0·020	0·184	0·003	0·037
9	0·463	0·121	0·002	0·020	—	0·022	0·036
10	0·090	0·163	0·009	0·084	0·020	0·023	0·037

Numbers 3, 5, 8, and 9 are mild tempers, and 10 is ingot iron.

Chemical Changes in Crucible Steel.—The chemical changes occurring during the melting of steel in crucibles

will depend chiefly on the composition of the metal, the extra materials added, and on the nature of the crucible in which the steel is melted. The materials added to a crucible are: iron, which may contain slag; oxide of iron in the form of rust on the surface of the metal; occluded hydrogen, carbonic oxide, and a certain amount of atmospheric air. The iron may contain carbon, silicon, phosphorus, sulphur, manganese, etc.; and, if spiegel-eisen or ferro-manganese is added to the charge, manganese will be additionally present. The crucible consists of clay, with some free silica and carbonaceous matter; and if plumbago pots are used, much graphite will be present in the crucible walls. The oxygen present will tend to form oxides of iron and manganese; but these oxides will not be able to remain in a graphite crucible, because the graphite will reduce them, forming carbon dioxide or carbonic oxide. But oxides of iron and manganese can form a fusible slag with silica. The slag formed in the crucible will be basic at first and exert a refining influence on the iron. The carbon will act on the free silica of the crucible, reducing it, in the presence of iron, to silicon, which will then combine with the steel. As the process proceeds, the slag will become more acid by taking up silica from the crucible. Carbon will also unite with the iron.

The reduction of the silica mentioned above practically only occurs in crucibles containing carbon, unless manganese is present, or more carbon than can combine with the iron. In clay crucibles containing only a small amount of coke dust very little silica is reduced, showing that the carbon in the iron is combined with the iron, and this is not available for the reduction of the silicon, unless an excess of carbon is present, as in very hard steels. Hence a charge of high carbon steel takes up more silicon than mild steel or wrought iron. Allusion already has been made to the

absorption of silicon during the killing stage, and that, when the killing is unduly prolonged, the metal becomes hard and brittle, due to the absorption of too much silicon, especially when graphitic crucibles are used. The manganese in the charge also energetically attacks the silica of the crucible, reducing it to silicon, without the assistance of graphite; hence the crucibles should be made to contain as little free silica as possible in graphite crucibles, and in clay crucibles free silica is an advantage to assist in killing. The presence of much manganese has a tendency to promote absorption of carbon from the crucible. Manganese not only absorbs silicon from the crucible, but on account of its affinity for oxygen prevents the reduced silicon from being re-oxidised. Manganese assists in forming a basic slag.

When hard steel is melted in a graphite crucible it will take up more carbon from the crucible, and in such metal graphite may be found to have crystallised out on cooling. If the percentage of silicon in the finished steel exceeds that of the manganese, hard steel, melted in a crucible low in carbon, may also show the appearance of graphite.

If the materials of which a crucible is made contain sulphur, as in pyrites, etc., such sulphur will probably pass into the steel, and crucible steel often contains a higher percentage of sulphur than the metal charged into the crucible.

The percentage of carbon and the casting temperature were formerly considered the principal agents responsible for the production of sound ingots; but these are only of secondary importance, though by no means unimportant. The principal prevailing cause is to be found in the relative percentage of silicon and manganese present in the metal at the time of casting. Aluminium has a similar effect to

that of silicon. The influence of these elements in the steel would be diminished by casting at a very high temperature, as then solidification would be retarded and the top portion become partly solid, while the lower parts were still evolving gases.

CHAPTER XXI.

BESSEMER PROCESS.

THIS process consists of blowing air through molten pig iron in a vessel, termed a converter, whereby the carbon, silicon, etc., are oxidised, together with some iron. This oxidation produces a high temperature, keeping the mass in a liquid state, and purifies the iron without the aid of ordinary fuel. Two distinct modes of working, employing totally different classes of pig iron, are adopted. In one, the converter is lined with acid material, generally ganister, and in the other the lining is of basic material, calcined dolomite being chiefly used. This is termed the basic Bessemer process, while the former is termed the acid process.

In the Bessemer process the increase of temperature goes on progressively from the moment of blowing to the conclusion of the blow. The oxidation and refining of the metal proceed simultaneously through the whole mass of metal, and it thus differs from reverberatory methods of refining, where the oxidation is greatest at the top. In the acid process practically the whole of the phosphorus and sulphur remain in the iron; hence only the purer varieties of pig iron can be employed. In the basic process the sulphur and nearly the whole of the phosphorus are

removed, in consequence of the basic slag. It will be seen, then, that the quality of the finished steel depends on the nature of the iron employed and the nature of the material with which the vessel is lined, as that determines the nature of the slag. The Bessemer process was first patented in 1855, and was described in a paper read before the British Association, in which the inventor claimed a method of making wrought iron without fuel. The excitement caused in all iron-making countries was immense, as it was thought that the wrought-iron industry was doomed, since the three tons of pig iron refined in a puddling furnace in twenty-four hours could be refined in the Bessemer vessel in twenty minutes.

The charge of pig iron is usually melted in a cupola ; but in some large works, where a blast furnace plant is available, the molten metal, instead of being first run into pigs, is run into a ladle fixed on a truck and run on rails, either to the Bessemer direct or poured into a large vessel, termed a mixer, which is capable of holding over 100 tons, and from this mixer the molten metal is conveyed to the converter (see fig. 114). The charge is run into the converter while it is in the horizontal position, the blast turned on, and the vessel rotated into the vertical position and kept there until the metalloids are removed. The metal is then in the condition of what is generally termed burnt metal, due to the presence of dissolved oxygen. This is largely removed by the addition of a manganese alloy, such as spiegel-eisen or ferro-manganese, which also recarburises the iron sufficiently to form steel.

Sir Henry Bessemer's great invention is not confined to the process of blowing air through molten pig iron, for the mechanical appliances suggested and invented by him for the carrying out of the process, were as necessary commercially to its success as that of the principle of the invention.

The first experiments were carried out in an ordinary air furnace, in which was placed a 40-lb. clay crucible, having a perforated cover, and through the centre of which a fire-clay tube descended nearly to the bottom. In this crucible 10 or 12 lbs. of pig iron were first melted. The clay tube was then inserted through the cover in order to convey a blast of air down into the molten metal. In this simple fashion Bessemer ascertained the important fact that molten pig iron could be rendered malleable by passing through it a blast of air. The first apparatus was kept hot by a coke fire. The first movable converter was spherical, chosen because that form presents the smallest amount of radiating and absorbing surface of any known form in proportion to its capacity. The twyer pipe entered the metal at an angle of 45 degrees, and was withdrawn from the metal before pouring. The next form was an upright cylindrical fixed vessel, a form which has been re-introduced in various shapes of late years by different inventors.

Bessemer now began to see the necessity of acting vigorously on the centre of the metal by the air, and to avoid blowing until the whole of the metal had been run into the vessel; also to be able to stop the blast at any period, and to resume the blow without any metal getting into the twyer. This led to the expedient of moving the whole converter on an axis, and thus raising the twyers above the level of the metal when necessary. Various shapes were tried with more or less success, still keeping in view the idea of pouring direct from the mouth and introducing the air at the bottom. Another idea was to dispense with the movable ladle, and to pour the metal direct into a fixed ladle, and thence into the moulds, which were moved on trucks under the ladle spout.

At this time the inventor perceived the great advantage of conserving the great heat of the ingots by covering them

when stripped with hot dry sand, from which the still red-hot ingots were wheeled to the rolls. This seems to be the first crude idea of the soaking pits afterwards so successfully applied by Gjers. The prevalent idea of Sheffield steel-makers at that time was that it was necessary to allow the ingots to get perfectly cold before any attempt was made to forge them, and if stacked in the yard and weathered for six months, so much the better.

Many modifications, as well as reversions to earlier types were tried, until the pear-shaped converter, supported on trunnions with a number of twyers and air chest fixed to the bottom, was evolved—a form and arrangement which is now so familiar. It was considered a great achievement when a simple converter, with what would now be termed primitive appliances, and operated by hand gearing, turned out ingots for making steel rails at £18 per ton.

We may broadly classify Bessemer vessels into two classes, viz., fixed and movable. The former kind has only been used to a limited extent, but the movable type is that generally employed. The fixed converter has been somewhat largely used in Sweden. It is of cylindrical form, with ten or twelve large twyers placed at a tangent to its circumference, so as to give a motion of rotation to the metal, and was successful in producing sufficient heat with their pure charcoal pig iron; but these fixed converters when once commenced have to go right on to the finish; also the tap-hole has to be broken open to discharge the metal.

The movable converter is capable of rotation in a vertical plane through an angle of 180 degrees or more, and is supported on a pair of trunnion arms, resting on standards. The movable converter thus affords great facilities for discharging the metal at the end of the blow, and also by turning down the vessel into a nearly horizontal position

the charge lies outside the blast from the whole of the twyers, and may remain there for a time after the blast is shut off.

The movable converter has been made in two forms, known respectively as the eccentric and the concentric

FIG. 94.

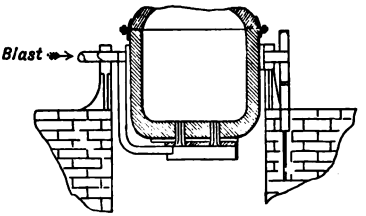


FIG. 95.

converter. The former is shown in Figs. 94 and 95, and the latter in Fig. 96. The eccentric vessel consists of a shell of wrought-iron plates riveted together, the neck being inclined at an angle of about 30 degrees to the vertical axis of the body. The centre of the body is enclosed by a stout iron band, to which is fixed two arms, termed trunnions, by which the vessel is supported on iron standards. One of these trunnions is hollow, to allow for the passage of the blast into the pipe that leads to the twyer box, which is attached to the movable bottom of the converter.

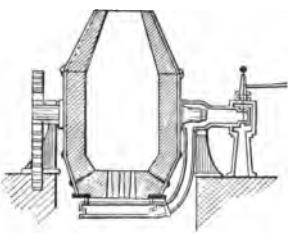


FIG. 96.

In the earlier Bessemer works two 3-ton converters were placed opposite each other with a deep circular casting pit between them. In the centre of this pit was an engine, with a vertical cylinder and a solid plunger piston, carrying

at its upper end a cross arm, formed of two parallel girders strongly braced together, to one end of which was attached the ladle, balanced by a counterpoise at the other end. Later practice dispenses with this pit, and the converters are placed on an elevated platform, so that the ingot moulds stand on the ground level. The capacities of modern vessels have been raised from 3, to 10, 15 and 20 tons. It must be borne in mind that the vessel must not only be large enough to hold this quantity of metal, but there must be sufficient space to prevent excessive loss of metal by ejectment during the boil, and the level of the molten metal must not reach to the level of the twyer holes when the vessel is in the horizontal position. An 8-ton converter will measure at the trunnions 8 feet 4 inches inside the casing, or 6 feet 10 inches inside the lining, the latter having a thickness of about 9 inches, whilst the shell plates are made $\frac{3}{4}$, $\frac{7}{8}$, and 1 inch in thickness, according to the capacity of the vessel. The size of the neck is important, for if the neck is too wide there is a loss of heat, and if too narrow the back pressure within the vessel is increased, and the duration of the blow prolonged.

Originally it was the universal practice to contract the shell of the vessel towards the bottom, because the bottom is the part that wears out soonest and requires the more often to be repaired, hence the smaller the bottom the less the amount of repairing material. Moreover this contraction of the bottom is a step nearer the spherical form, which has the minimum heat-radiating surface. But this was found to be false economy, as the depth of metal above the twyers was found to increase the wear of the bottom, probably because the blast pressure is less able to keep the iron oxide away from the mouth of the twyers. Moreover, the shell lining is more liable to be eaten away near the bottom, and this is difficult to repair. It is customary now

to build the converter with straight sides, as in Fig. 97. They are cheaper to build and keep in repair, and as the bottom of the sides is farther from the twyers it is less liable to be corroded. The contracted bottom was intended to serve another purpose, viz., to prevent the lining from dropping from the sides when the bottom was removed, but with the straight-sided vessel this can be prevented by having a stout ring of angle-iron at the bottom.

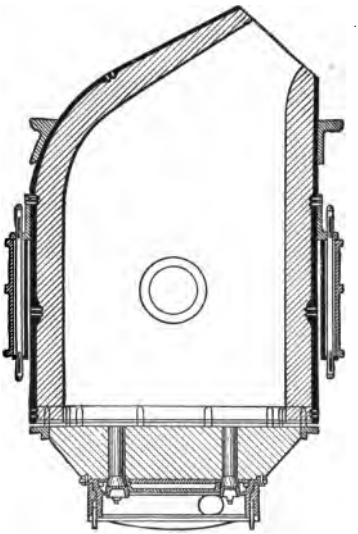


FIG. 97.

As the bottom of the converter is the part subjected to the greatest stress, as well as to the corrosive action of the oxide of iron formed by the action of the blast on the molten iron, great attention has been paid to the best form of bottom, and to arrangements for expeditiously removing it when defective. It is, therefore, detachable from the body, can be removed in a comparatively short time, and a fresh bottom affixed in its place. Moreover, this further obviates the necessity of running in "slurry" or fluid ganister around the joints, with its defect of being liable to leave weak spots around the twyers, through which the metal may break. The rapid wear of the bottom may be judged from the fact that one only lasts about 20 to 30 heats, while the rest of the lining may last the best part of a year. In the bottom itself we have,

besides the twyers and the refractory lining, the wind-chest which receives the blast from the goose-neck and distributes it to the butt ends of the twyers. The lid or bottom plate must be large and capable of being quickly removed, so that no time may be lost in examining it between the heats, and tightly fitting so as to prevent loss of blast. The twyer plate which forms the upper side of the twyer box, is perforated with a number of holes—ten in the smaller sized vessels and up to double that number in the largest vessels—pitched at equal distances from each other (Fig. 98), and into these holes are fixed conical fire-clay twyers, each perforated with 10 or 12 holes, three-eighths of an inch in diameter, so as to distribute the blast in small jets into the fluid metal. The lower ends of the twyers stand out a little below the guard plate, but each one is held up in contact with the plate by stops carried on horizontal arms, which can be turned aside as required for convenience of removal and renewal. Thus after a faulty twyer is removed a new one is quickly inserted, first luting it round with fire-clay, then driving it into the opening in the guard plate, securing it with the stops before mentioned, and then running in the slurry so as to make a tight joint: after drying, the vessel is ready for another charge.

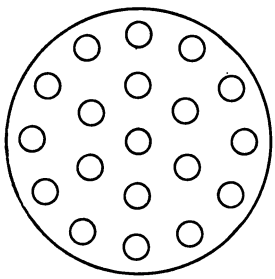


Fig. 98.

The Holley movable bottom is a great improvement on the old system. This bottom is previously dried and raised to the body by a hydraulic lift, and the annular irregular space forming the junction of the bottom with the body of the vessel is inclined at an angle of about 45 degrees, and is then readily accessible from the outside, so

that it can be filled up with cakes of ganister, well rammed in.

The rotation of the vessel is effected by a pinion, driven by a rack, which is keyed to the end of the piston rod of a hydraulic cylinder (Fig. 99). By the movement of the ram the vessel can be rotated through about 270 degrees, so that any position from the upright one to the extreme opposite position can be obtained. Three chief

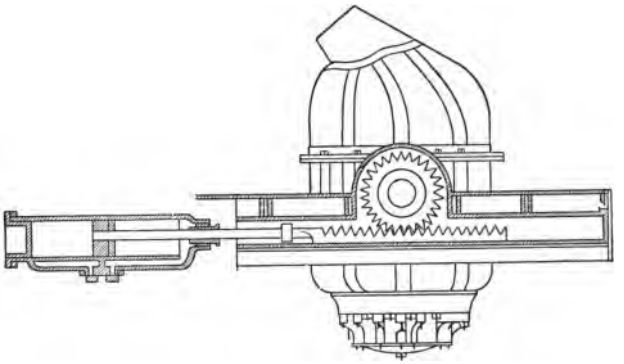


FIG. 99.

positions are required, viz., vertical, horizontal, and inverted. The upright position is used during the blow, the horizontal position when charging, and the downward position when tipping out the residual metal and slag. The rack and hydraulic piston are required to be double acting, and their action is controlled by a valve, generally worked by hand, and placed at some distance from the vessel.

The lining of the acid Bessemer vessel in this country is a siliceous sandstone or ganister, containing from 85 to 90 per cent. of silica, and which occurs below the coal measures. This is ground fine, mixed with water, and rammed in between a central wooden core and the iron shell of the vessel. In America the lining consists of a

mixture of 60 per cent. of crushed quartz, 25 per cent. of fire-clay, and the remainder of ground-up fire-bricks or other siliceous material. This lining lasts for 400 to 500 heats, while the British lining lasts double the time, but we must take into account the more rapid working of the American vessels.

Concentric Vessel.—In the eccentric vessel a large amount of metal can lie in the belly, without running into the twyers or out of the nose, and it to some extent prevents slopping. When the method of using metal direct from the blast furnace was introduced a modification of the converter appeared necessary, so that it might receive molten iron from the blast furnace ladle when turned away from the pit, and receive spiegel-eisen from the cupola when turned towards the pit. This is readily done with the concentric, but not with the eccentric vessel. The concentric vessel is, however, required to be larger than the eccentric one, in order that when turned down it may hold a given charge on either side without running out at the mouth or into the twyers. The ratio of the capacity of the concentric to the eccentric vessel is as 3·5 to 5, but in consequence of the greater size less slopping occurs, and much of the metal ejected during the boil falls back again into the vessel. Now the path over which the metal runs into the converter is very highly heated, and the slag afterwards formed, more easily corrodes this more highly heated portion; hence the advantage of equalising this wear by pouring alternately into each side of the vessel. The concentric converter is generally made in four parts, connected by bolts and cotters for easy detachment. Fig. 96 is a vertical section of a 10-ton converter. The weight is about 40 tons, the wrought-iron plates one inch thick, with inch rivets and strong straps; the four parts are connected by pins and cotters. The belt and trunnions are in two

pieces, formed of cast iron box sections; the trunnions are 21 inches long; the belt weighs 11 tons, and is 10 feet 8 inches in internal diameter. The tipping gear consists of a worm-wheel 8 feet in diameter, gearing into a screw of 4½ inches pitch, which receives its motion directly from the cranks of a pair of hydraulic engines, mounted on one of the converter standards. This allows of the vessel being turned over in either direction. A larger converter of this kind for 15-ton charges is 24½ feet high and mounted on piers 20 feet above the ground. Such a vessel may weigh from 60 to 70 tons. A wide nose may be advantageous from the point of reducing loss from ejected metal; but the narrower the nose the higher the working temperature, and the greater the amount of metal the vessel can hold when in the horizontal position.

The proper arrangement of a Bessemer plant is a matter of great importance, and the particular arrangement will largely depend on whether the plant is a small or a large one, for in the latter case the question of rapid handling of immense quantities of metal is all important. The arrangement of the plant will also be modified when the iron is employed direct from the blast furnace, instead of being melted in a cupola. The operations may be classified under four heads: 1. Melting in the cupola. 2. Bessemerising in the converter. 3. Casting the metal into moulds. 4. Lining vessels and ladles, and repairing. For small plants it is necessary that the cost of the installation should be as low as possible. The position of the cupola must be such that the metal can flow by gravity from the tap-hole to the Bessemer vessel; hence it is placed at a higher level. If the cupolas are too near the converters the workmen are exposed to excessive heat, being between two great fires. On the other hand, if the cupolas are too far away the long runners tend to chill the

metal too much and some of it will solidify, causing much waste. In some works this difficulty has been

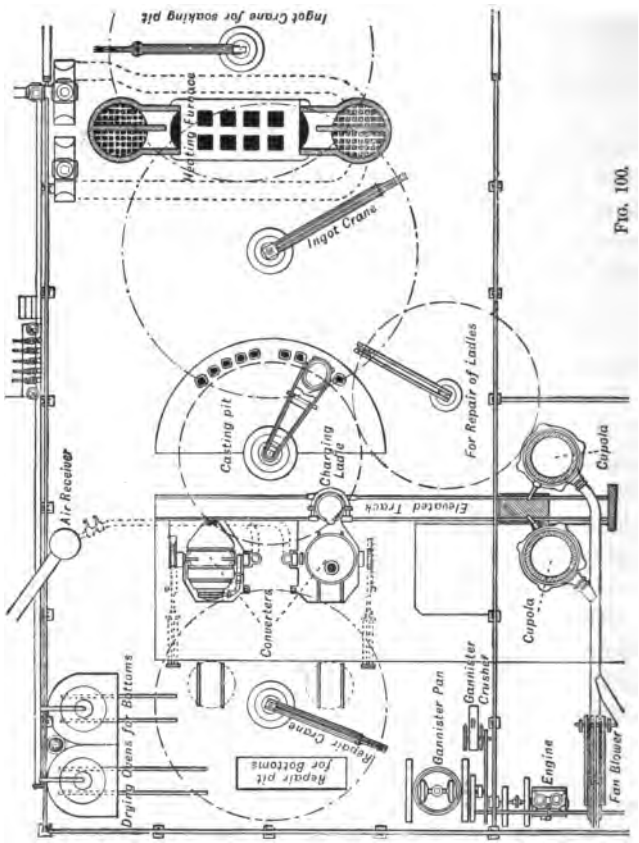


FIG. 100.

overcome by using travelling iron ladles to convey the cast iron from the cupola to the converter, either by running on a track or by means of a crane, which admits of tipping the molten contents of a ladle into the converter.

Fig. 100 shows the plan of a good arrangement for a small plant. Two cupolas deliver the molten cast iron to a ladle, which runs on an elevated track, and delivers the metal to the converters. An ordinary casting ladle receives the steel, which is run from it into moulds standing along the rim of the semicircular casting pit. From this pit the ingots are stripped and raised by a crane, which deposits them in soaking pits, from whence they are conveyed to the rolls. The refractory materials are prepared in a space behind the vessels, and near to this is the engine that provides the power for blowing, and actuates the machinery for crushing the refractory materials.

Fig. 100A[1] shows a section of a Bessemer plant at the Cambria Iron Works, U.S.A. It is of the Forsyth type, with its broad, shallow pit, served by three ingot cranes. The vessels stand back from the pit, and the casting ladle is carried from vessels to pit and back, over a short intermediate transfer rack. The cupolas are 8 to 10 feet in outside diameter, and from 14 to 24 feet high from the bottom of the inside to the charging door. The blast is worked at a pressure of 10 to 12 ounces per square inch. The larger ones melt 16 tons of pig-iron per hour, with a fuel consumption of 6 to 7 per cent. of the iron melted. This is made possible by the oxidation of some of the silicon in the pig iron.

The ladle employed for receiving the steel from the converters is made of wrought-iron plates riveted together and lined with similar material to that of the converter. The lining slopes from all parts of the bottom towards the tap-hole, which is nearer to one side than the other, so that the fire-clay nozzle can be manipulated easily by a lever from the outside (Fig. 101). This plan is necessary for teeming the molten steel, for if the steel were poured

[1] Howe, *Jour. Iron and Steel Inst.*, No. 11, 1890.

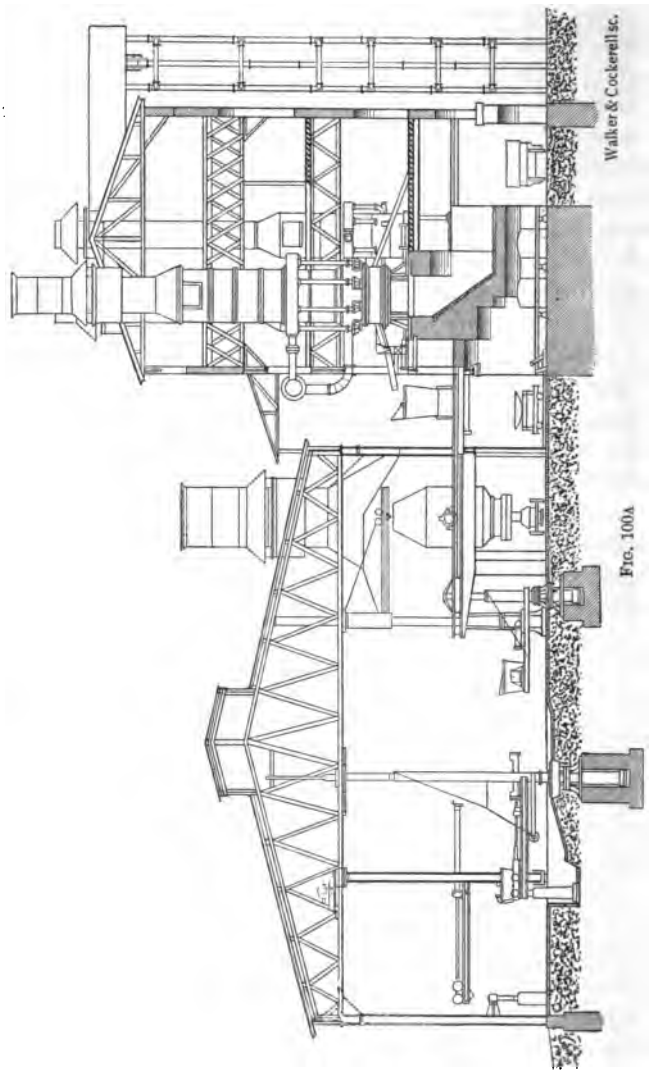


FIG. 100A

over the edge, as in foundry practice, the solidified slag which floats on the top of the steel, and which acts as a cover to keep the heat in the metal, would also pass into

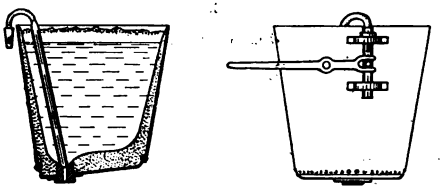


FIG. 101.

the mould. Moreover, it would be difficult to pour rapidly, much scrap would be made, and the fall of the stream of metal would be excessively long, cutting the mould bottom and agitating the metal. The tap-hole is

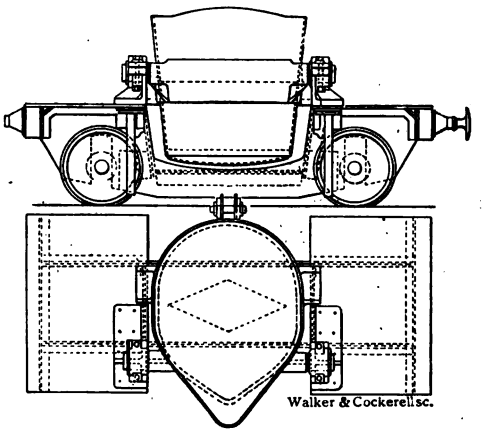


FIG. 102.

closed or opened by a fire-clay stopper or nozzle attached to the end of an iron rod, coated with clay, which bends over and downwards from the top edge of the ladle, so that by connecting this "goose-neck" or "swan-neck" as it

is termed, with a suitable lever, the stopper can be raised or depressed for letting out or stopping the flow of metal from the ladle into the several moulds, over which the tap-hole is brought in succession. Care must be taken that the metal does not wash the sides of the mould in its descent to the bottom, otherwise unsound or sticking ingots will result.

Fig. 102 is a section of a side tipping ladle, mounted on a bogie carriage. It is carried by a cast steel belt with trunnions running in frames, which slide on transverse racks. On each trunnion is keyed a wheel gearing into the rack, and motion is communicated to the trunnions by a hand-wheel and worm gear. In the act of tipping the ladle moves forward on the track so as to clear the road, and it may be tipped on either side.

Acid Process.—It has already been stated that the acid method of working is only applicable for pig iron very low in phosphorus, but sufficient silicon must be present to yield the necessary heat. The varieties of iron used in this country are those smelted from haematite or magnetite ores, not higher grade than No. 2. Since the purification of the crude metal is effected by the oxygen of the air, it is obvious that the greater fluidity of grey iron is advantageous, as the plasticity of molten white iron is liable to interfere with the free passage of the air through the molten metal. In fact white iron can only be treated with increased waste, especially as it is deficient in silicon. Moreover, white iron is often much higher in sulphur than grey iron. Also the carbon being in the combined form the production of carbonic oxide takes place at too early a stage of the process, and not being present in sufficient quantity, prevents the attainment of the requisite high temperature.

The chief essentials then, in the composition of the pig

iron are, a very low percentage of sulphur and phosphorus, with about 2 per cent. of silicon. Both silicon and manganese can be practically removed by the blow, as both elements are oxidised and unite to form a slag. The following analyses give the composition of some Bessemer pigs:

	Carbon.	Silicon.	Manganese.	Phosphorus.	Sulphur.
Charcoal pig, -	3·90	1·96	3·06	0·04	0·02
Greenwood, - -	3·75	1·76	0·13	0·38	0·14
Snelus, - -	3·27	1·95	0·09	0·05	0·14
Staffordshire, -	3·94	1·61	0·12	0·02	0·03
Jordan, - -	4·40	1·81	1·08	0·01	0·04
American, - -	3·10	0·98	0·40	0·10	0·06

Mr. H. M. Howe stated in 1890 that while there are American mills where 2 per cent. or more of silicon is present in the charge, the majority use less than 1·75, and what appears to be the most characteristically American practice has habitually but from 0·66 to 0·9 per cent. of silicon. In order to blow iron with such little silicon successfully, the heats must follow each other quickly, and vessels and ladles must be hot. He considers that as far as convenience of blowing is concerned, 1·25 per cent. of silicon is the best proportion. Metal with 0·5 per cent. of silicon has been blown in Sweden, but this is only done when the initial temperature is very high. For low silicon then, quick blowing and short intervals are necessary.

The length of blow depends on the composition of the iron, the blast pressure, and the depth of metal in the vessel. The American blast pressure is 20 to 25 lbs. per square inch, and 2 to 4 square inches of twyer holes per ton of metal in the charge are required, which is about the same as European practice. The time of a blow is about 10 minutes, in consequence of the low silicon, and the

shallow depth of the bath of metal. With "direct" metal the blow is a little longer. The Holley type of plant is usually employed, with its shallow pit and vessels raised on a gallery above.[1]

In the acid process almost the whole of the effective heat comes from the combustion of the silicon, and the greater the percentage of silicon, the hotter the charge, the longer the blow, the greater the loss, the more expensive the repairs and maintenance, and when the silicon is very high the poorer the quality of the steel. On the other hand, too low silicon causes cold heats, heavy skulls, and bad working generally. A percentage of 1·5 of silicon should give the requisite heat.

The combustion of the metalloids in the converter may be said to take place in two stages: 1. Scorification, during which stage the graphite passes into combined carbon, silicon becomes oxidised, and silicates of iron and manganese are formed. This stage lasts about five minutes. 2. Ebullition, during which stage the carbon is rapidly oxidised by the blast, carbonic oxide being evolved in large quantities, this stage lasting about 6 to 10 minutes. The first stage is accompanied by a reddish-yellow flame, the second by a more brilliant display of flame and sparks, and numerous small detonations. The first stage yields but little flame because the products are not gaseous (oxides of iron, silicon, and manganese). The products of the second stage are gaseous (oxides of carbon) and so are accompanied by a greater evolution of flame. As soon as the carbon has gone, the flame drops. An experienced workman detects this instantly and stops the operation, or the iron would rapidly oxidise. A former practice was to stop the operation before all the carbon was burnt off, leaving sufficient carbon in the iron to constitute the desired quality of steel. But this

[1] *Jour. Iron and Steel Inst.*, No. 2, 1890.

practice is but little pursued now in this country as it is much better to eliminate all the carbon and afterwards add the requisite amount. This is done by using spiegel-eisen, which serves the twofold purpose of yielding carbon to the iron and removing the dissolved oxygen by means of the manganese. The latter not only acts on the dissolved oxides but probably also neutralises the effects of the sulphur: moreover it assists in making a liquid slag. When mild steel is desired, ferro-manganese is used instead of the spiegel-eisen. The metal at the end of the blow resembles burnt iron. It is red-short, unweldable, and unforgeable at a red heat. The manganese removes the cause of these defects. The temper or hardness of the steel depends on the quantity of carbon introduced into it.

There are three considerations which must be taken into account in regulating the temperature: the composition of the iron, its quantity, and the rapidity of the blow. The first is less under control than the two latter. In England the aim is to keep the percentage of silicon low, whilst in Sweden the reverse is the case, since the ores are smelted with charcoal, and manganese is usually present. Now in this country the ores are smelted with coke, which introduces sulphur into the charge, and to keep the sulphur out of the pig iron the latter must be grey, which is chiefly due to silicon. Thus, if the silicon is too low the sulphur in the iron will probably be too high, causing the steel made from it to be red-short. If the silicon be high the blow will be too hot and cold scrap iron will require to be added to the charge in the converter. If the metal be blown too hot, too much silicon will remain in the steel. In charcoal pig iron, especially from Swedish ores, the sulphur is very low and the presence of manganese tends also to prevent this sulphur passing into the steel. But ores smelted with charcoal produce pig iron low in silicon,

therefore the aim of the smelter is to reduce as much silica as possible.

When the amount of manganese in Bessemer pig iron is upwards of 2 per cent., as is often the case in Sweden, the direct method is adopted; that is, the blow is not continued till the whole of the carbon is burnt off, as in England, but stopped when the metal contains the desired amount of carbon, which can be judged by the aid of the spectroscope and the colour of the slag. The amount of manganese remaining in the steel varies from 0·1 to 0·3 per cent.

Seeing then that the acid process cannot remove sulphur and phosphorus, a special brand of pig iron is required and has become a necessity, and such iron is now sold as Nos. 1, 2, and 3 Bessemer pig iron. The presence of manganese in such pig iron is an advantage, since it assists as a heat producer, and shields the iron from oxidation during the blow, while its oxide readily unites with silica.

The slags produced in the acid process vary in composition with the iron used, and consist of a heterogeneous mixture, consisting of the well-fused portions of the slag proper, cementing together siliceous infusible matter, detached from the sides and bottom of the converter. The composition of the slag from a given blow is as follows:

	I.	II.	III.	IV.	V.
Silica, - - -	47·0	52·0	47·0	47·0	72·0
Alumina, - -	3·7	3·0	3·0	3·5	2·5
Ferrous oxide, -	7·7	5·5	16·0	15·5	21·0
Manganese oxide,	37·0	37·0	32·0	32·0	3·0
Magnesia, - -	1·5	0·5	0·5	0·6	0·1
Lime, - - -	3·0	1·7	1·2	1·2	1·04
Sulphur, - -	0·03	0·01	0·01	0·01	—

The above are only approximate numbers, as the composition varies in different works. No. I. represents the com-

position at end of first period. No. II. At end of the boil. No. III. Before the addition of spiegel-eisen. No. IV. After the addition of spiegel. No. V. shows the composition of the siliceous mixture emptied from the converter at the end of the operation. The nature of the slag at different periods of the blow has been closely studied, and affords to experienced operators valuable evidence as to the progress of the refining. It will be seen from the above analyses that during the first and second stages, and until near the end of the boil, the silicon and manganese are being rapidly oxidised and passed in to the slag, while the iron during this period is only oxidised to a small extent. At the end of the blow, before the addition of the manganese compound, the iron has been rapidly oxidised, as shown by the large increase in ferrous oxide.

A slag test was formerly used in Sweden and Austria by introducing an iron rod into the slag in the converter, and, upon withdrawing the rod, the adhering slag was found to present different appearances, according to the degree of decarburisation attained by the metal. The slag always presents a peculiar brownish appearance so long as the metal retains any carbon, whilst it becomes totally black, with the lustre characteristic of ferrous oxide, immediately the whole of the carbon is removed, and the various intermediate percentages of carbon are indicated by corresponding tints of the slag: thus, 0·75 per cent. of carbon is indicated by a lemon-yellow coloured slag, which changes to orange as the carbon falls to 0·6 per cent.; it becomes light-brown with a content of 0·45 per cent.; dark-brown with 0·3 per cent.; and bluish-black with 0·15 per cent. of carbon.

The gases escaping from the mouth of the converter, as shown in the accompanying table by Mr. Snelus, indicate that at the commencement of the blow, when the tempera-

ture is low and the flame only moderately luminous, the carbon of the metal is being burnt to carbon dioxide, with an entire absence of carbonic oxide; but after an interval of one to two minutes the carbon dioxide has decreased and some carbonic oxide is present. The proportion of carbonic oxide continues to increase with a corresponding diminution of carbon dioxide as the temperature of the metal rises. During the boil a very high temperature prevails, and almost the whole of the carbon is burnt to carbonic oxide. At the end of the blow, when the decarburisation is complete, the stream of gas given off is composed very largely of nitrogen. Carbonic oxide is more stable at elevated temperatures than carbon dioxide when in contact with metallic iron, and Mr. Bell suggests that this may account for the fact that, whilst carbon dioxide is present in the earlier stages of the blow when the temperature is the lowest, it is almost entirely replaced by carbonic oxide in the later stages when the temperature is much higher.

ANALYSES OF GASES FROM THE MOUTH OF THE CONVERTER (Snelus).

	Time after the commencement of the blow					After addition of Spiegel.
	2 min.	4 min.	6 min.	10 min.	14 min.	
Carbon dioxide, -	10·6	8·6	8·2	3·6	1·34	—
Carbonic oxide, -	—	4·0	4·4	19·5	30·36	82·0
Oxygen, - -	1·0	—	—	—	—	—
Hydrogen, - -	—	0·8	2·0	2·0	2·00	3·0
Nitrogen, - -	88·4	86·6	85·3	74·8	66·30	15·0

The time required for a blow is generally less in America than in this country. The blow proper depends on the proportion of carbon and silicon in the metal, the weight of the charge, the number and size of the twyer holes, and the pressure of the blast. Howe states that Forsyth has

made 7 ten-ton heats in an hour, and 73 heats in 12 hours. This is at a rate of less than 10 minutes per heat. Small Swedish vessels blow a heat in five minutes, by using a large twyer area.

Mr. J. M. While,[1] in the *Journal of Iron and Steel Institute*, 1901, describes a new Bessemer plant for the Barrow Haematite Steel Company's works, including converters, cranes, ladles, and ingot stripper. The Bessemer shop comprises four converters, each of 20 tons capacity, arranged in a row and facing the pit. They are made of 1-inch steel plates, and encased by wide cast steel rings, on to which the trunnions are gripped, being also fastened to them by rivets. The converters are elevated sufficiently to permit of the ladle, standing on a crane below, receiving the steel, and also of a bogie on a road beneath the converter receiving the slag. Each converter is actuated by a pair of vertical hydraulic rams, with racks and pinions acting in opposite directions.

In front of the converters is a platform, to which access is obtained by an inclined roadway, so as to bring the molten iron from the mixer in ladles of 18 tons capacity each. These ladles are made of steel, five-eighths of an inch in thickness, encased like the converters, in rings. The trunnions are not central, but are in such a position as will, during tipping, throw forward the contents into the converter (see Fig. 102). A locomotive places the ladle in front of the converter mouth, a hook engages itself on to a pin fastened on to the ladle and lifts it gradually until the whole of its contents are poured into the converter. Spiegel is charged into the converter in the same manner, the cupola for melting it being at one end of the platform. The appliance used for lifting the ladle consists of a pair of rams, supported by lattice girders, 21 feet above the staging, to which are

[1] *Jour. Iron and Steel Inst.*, No. 1, 1901.

attached chains for serving the converters. Scrap is charged chiefly before running in the metal, but when necessary, scrap is added afterwards from the platform.

Beneath each converter is a lift, used for lifting and fixing the bottom in position. Over this lift is a roadway, on which at all times stands a truck, which receives the slag from the converter. Two transfer cranes are situated below, on which are placed the ladles for receiving the steel. These transfer the ladles to a central crane, which carries them to the casting moulds. There are also smaller cranes for changing ladles and for other work.

All the moulds are placed on bogies (see Fig. 116), each bogie carrying two. They move forward under the nozzle of the ladle as required, the central crane remaining stationary. As the position of each mould has to be very exact, so as to prevent a cutting action of the fluid metal, as well as loss during pouring, the bogies are moved along by means of a finger fixed on a ram, situated below the floor level. All the moulds are of one size, each holding two tons. When the ingots have remained in the moulds about ten minutes the bogies are drawn forward to the ingot stripper, which strips the moulds from the ingots and places them on an empty bogie ready for another cast. The stripped ingots are taken to two gas-heated pits by a locomotive. These pits take the form of a long passage 4 feet 6 inches wide and 7 feet deep, at either end of which is a regenerator. Each pit holds 20 ingots, four under each lid. When the ingots have remained in the pit a sufficient length of time they are lifted out, placed on live rollers, and conveyed to the cogging mill.

Mr. While claims the following advantages over the old system:

1. The use of molten metal in larger quantities, saving haulage and ladle skulls.

2. Pouring metal direct into the converter, and thus saving use of runners.

3. Blowing larger quantities of metal, reducing cost of bricks, twyers, steam and hydraulic power.

4. Transfer of all material to one central crane, saving labour and hydraulic power, and providing hot ingots in a constant stream.

5. The casting of ingots in moulds placed on bogies, instead of using casting pits, saving labour and power, and being safer.

6. The ingot stripper saving labour and moulds. The ingots are conveyed to the mills by a locomotive, saving labour.

7. The use of heated pits, saving loss by oxidation, fuel, and labour, and expediting work.

The saving to the company by the use of the above mentioned plant over the older one is about 2s. 5d. per ton of ingots produced.

In addition to the above saving of expense, the original idea in erecting this new plant was to emulate American practice, to blow the heats in less time than is customary in this country, therefore the diameter of the converter bottom was enlarged so as to use a larger number of twyers and have a shallower bath. Each vessel has 33 twyers, each twyer 19 holes, five-sixteenths of an inch in diameter. It was hoped that this shallower bath would so shorten the blow that the bottoms and lining would run for a longer period, probably 20 to 30 blows. The result was contrary to expectations, for while the duration of the blow was reduced to 8 or 10 minutes, the blow was so hot as to be practically unmanageable, even when cooled by steam and the addition of scrap. The amount of metal thrown out of

the vessel was 20 to 25 per cent. of the charge. The steel was so hot as to destroy the bottoms and moulds in one cast, and the resulting steel worked badly. Fast blowing, therefore, in an acid-lined converter, and using Barrow iron, is not practicable. The number of twyers was then reduced, the depth of the bath increased, and the time of blowing increased to 15 minutes. This was not sufficient, and not until the time of blowing was raised to 20 or 25 minutes and the depth of the bath of metal further increased, was the advantage of the plant obtained, and steel of the best and most uniform quality produced. This proves that the rapid blowing, as used in America, is not suited to the iron produced in this country, and to the local conditions that prevail here.

Fixed Converters.—These are generally of small dimensions, and more wasteful in producing steel than those made on the larger scale. The blast is introduced at the side instead of at the bottom. This arrangement produces a large amount of brown smoke, and more iron is wasted in the early stages than with vertical blowing. Moreover, the momentum of the current of air is so slight, and it has to encounter so heavy a mass of iron, that instead of penetrating any great distance into the metal, it rises in bubbles close to the sides of the vessel. It also cuts a groove into the lining where the slag passes upwards in contact with the sides of the vessel. This results in a portion of the metal in the centre not being properly acted upon, and this, but for the centrifugal action of the blast, would not be acted upon at all. Small quantities are only acted upon and converted with difficulty, with great loss of heat, unless the metal is overcharged with silicon.

In fixed converters the principal points of novelty are in the arrangement of the twyers, the preventing of the metal running into the twyers, or being overblown while tapping,

and the slag-hole for removing the slag during the boil. Clapp & Griffiths close the twyers by plugs and slides actuated by pistons. Hatton and others partially close the blast-valve whilst tapping. Another plan is to incline the twyers so that their outer ends may be higher than the surface of the metal in the converter, and thus admit of the blast being shut off entirely at the conclusion of the blow.

Swedish Fixed Converters.—These were made to hold 25 to 30 cwts. They were 4 feet high, 4 feet internal diameter, and covered with a dome, having a long oblique neck for the escape of gases. They had 20 twyers, each having seven-eighth holes for the blast, placed horizontally and arranged equally round the converter. They were slightly inclined so as to make the charge rotate. The blast pressure was 6 to 8 lbs. per square inch. The blow lasted about 10 minutes, and the loss during conversion was about 12 per cent.

Clapp & Griffiths Converter.—The twyers in the Swedish vessel were placed close to the bottom, thus causing the metal to be somewhat overblown while being tapped. In the Clapp vessel the twyers were raised to about 10 inches above the bottom, so that when about half the metal was tapped out the twyers were out of the metal.

The ordinary converter is about 5½ feet internal diameter and 10 feet high, lined with silica bricks, and provided with from four to six horizontal twyers, fitted with valves for regulating the blast. The twyers are arranged about 9 inches above the floor of the converter, and about 5 inches below the surface of the metal when charged, which enables a soft blast of 5 or 6 lbs. per square inch to be used. As the slag rises, it is run off through a slag-hole during the intermediate stages of the blow. At the conclusion the metal is tapped as from a cupola. Ferro-manganese is then

added to the metal in the ladle to form mild steel. The process appears to almost completely eliminate the silicon, but leaves the phosphorus untouched, so that good haematite pig iron must be used. The more the bottom is worn, the nearer are the twyers to the surface of the metal, with the consequent greater waste of iron and greater heat of the steel. The chemical reactions are the same as those in the ordinary Bessemer converter. The percentage of silicon in the pig iron must be rather higher to remove the excessive amount of oxide of iron.

Howe summarises the defects of fixed converters thus: (1) They do not readily permit of bottom blowing, hence greater loss of iron during conversion, and a faulty twyer would be liable to spoil the whole charge, while in a movable vessel the metal could be easily tilted away by its rotation. (2) In side blowing the charge must all be tapped if a twyer becomes faulty, and the metal is then simply scrap. (3) The metal has to be tapped instead of poured, and the proportion of carbon is less under control because the time of tapping is longer than that of pouring. (4) Only mild steel or ingot iron can be made, because the recarburisation cannot be done in the vessel, and the manganese alloy is therefore added to the ladle.

Small converters seem to be specially suitable for works which do not possess the means of dealing with the whole of the output of larger vessels. The low carbon steel made in small quantities in fixed vessels seems to contain less silicon than that from the larger movable ones, but there is less control over the quantity of carbon.

Robert's Converter.—Fig. 103. This, although a movable converter, is only adapted for small charges, varying from 1 to 3 tons. The blast is introduced near the upper surface of the metal, and the twyers inclined at different angles, so as to give the metal a rotatory motion. The vessel itself is

tilted during the first half of the blow, and turned more vertically as the operation proceeds, in order that the blast may be less strongly localised. This converter is mounted on trunnions and revolved in the usual way, but by means

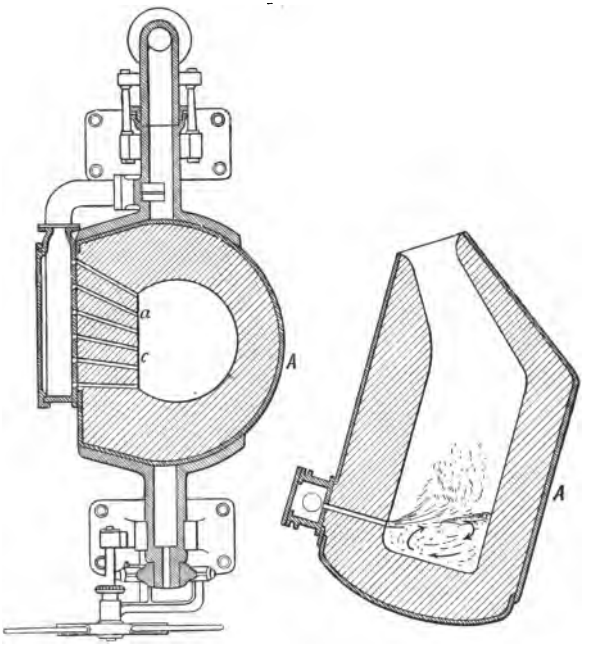


FIG. 103.

of hand gearing. The advantages claimed for this converter are: that no expensive blowing plant is necessary; the slag and gases separate better from the metal; a higher temperature is attained, enabling castings to be made; the process can be stopped at any given moment, and any kind of steel can be made, from the mildest to the hardest. The loss of metal in the Robert converter seems to be as great as in the fixed vessels, which averages about 20 per cent.

The position of the twyers high up in the bath is a disadvantage, in that it leads to increased loss of metal by oxidation. The reduced pressure of blast is an advantage common to all processes of this type.

Walrand Legenissel Process.—This is a modification of the Robert process, in which a miniature Bessemer converter of the ordinary type is used. The pig iron must contain about 3 per cent. of silicon, although, when the vessel is once heated, a pig containing 2 per cent. of silicon may be used. If very hot metal is charged into the vessel a corresponding reduction in the silicon may be effected. The metal must also be practically free from phosphorus. The carbon only slightly disappears during the earlier stages of the blow. The pig iron used, as in all small converters, must be of a regular character and of suitable chemical composition. The bath must be hot, if the process is to be satisfactory. The vessels employed are of the Bessemer bottom-blown type, and refine molten pig iron in the usual way. Just before the flame drops, they are turned down and a certain amount of 10 per cent. of ferro-silicon is added. The metal is again blown for a short time, forming an "after-blow." Ferro-manganese is then added and the metal run into ladles in the usual way. About 20 per cent. of the cupola charge consists of steel scrap. In blowing, the converter is turned down just before the drop of the flame so as to leave sufficient carbon to act as an index in the spectrum during the after-blow. The steel is said to be satisfactory in every respect; the carbon, manganese and silicon are well under control.

Side versus Bottom Blowing.—In the arrangements for introducing the blast to the Bessemer vessels previously described, two methods have been employed: blowing from the bottom, where the blast passes through the whole of the

metal, and blowing through the sides, where the blast passes only through a portion of the metal, leaving the portion below to be oxidised by conduction downwards, or by imparting a rotatory motion to the metal by introducing the blast in a tangential direction.

The disadvantages of side blowing are: the lack of uniformity throughout the bath, the action being strongest at the sides, so that the central parts are less decarburised than the outside parts; and although the different portions are mixed at the time of pouring, the incorporation is never so complete as when the thorough mixing is effected in the converter, as is the case in bottom blowing. Moreover, the metal where the blast enters is more highly oxygenated than the central portions, and this iron oxide is not afterwards completely reduced, but partly escapes in the form of a brownish-red smoke. The loss of iron is therefore greater than in the case of bottom blowing, especially in those vessels where the twyers are high up and therefore nearer to the surface of the metal.

Another disadvantage is, that as the bottom wears away, the blast entrance is brought nearer to the surface of the metal, with a consequent greater waste by oxidation and greater heat of the blow. This tends to destroy the constancy of the conditions in the bath, and, to rightly judge of the point when complete decarburisation is effected, the conditions should be constant as regards the blowing. In the Robert converter, as before explained, this is compensated for by tipping the vessel according to circumstances. Of course this defect of wearing away of the bottoms could be remedied by more frequent repairs, but that adds greatly to the expense, and, as shown in the case of larger vessels, the corrosion of the bottoms is the most serious item of expense. Also the life of shell linings is shorter in side-blown than in bottom-blown vessels. Side-

blown vessels are now but little used, owing to the above defects.

The advantages of side blowing are: saving of blast, which means less power and less fuel, saving of labour, longer life of the bottom linings, and the production of a high temperature.[1]

Basic-Bessemer Process.—This process is conducted in the ordinary Bessemer converter, but the vessel is lined with a basic material, instead of an acid material, as in the acid process. In consequence of the basic lining the slag produced is also basic, and, as a basic slag will take up elements whose oxides are of an acid character, iron rich in phosphorus can be refined in a basic-lined vessel, because phosphoric oxide readily unites with bases, such as lime and magnesia. But basic material can only take up a certain quantity of acid; and if much silica is present the base will be saturated by it in preference to phosphoric oxide, and an excessive amount of lime will in that case be necessary, if the phosphorus is to be removed from the iron. But as the amount of base is increased the melting-point of the slag is raised, as well as being excessive in quantity. This entails a great amount of heat to keep the slag melted, and an extra large vessel to hold the greater quantity. An increase in the size of the vessel is a great addition to the cost as well as an increase in the working expenses. The pig iron, therefore, must only contain a moderate amount of silicon; and as the oxidation of the phosphorus produces sufficient heat to keep the iron liquid, it can take the place of the silicon in the acid process, as a heat producer.

Now, grey pig iron generally contains too much silicon; and while such metal is admirably adapted for the acid process, it is unsuitable for the basic process, although it

[1] Howe, *Metallurgy of Steel.*

may also be high in phosphorus. It is therefore found advisable to use white pig iron, which contains less silicon than grey pig iron, and at the same time is often highly phosphoric. A highly suitable one should contain 3·2 carbon, 0·5 silicon, 2·2 phosphorus, and 1·5 manganese per cent. The following analyses show the kind of pig iron used for the basic process in different countries:

	Carbon.	Silicon.	Phosphorus.	Manganese.	Sulphur.
Westphalia, -	3·5	0·54	1·2	0·6	0·15
Eston, - - -	3·6	1·70	1·6	0·7	0·06
Rhenish, - -	3·3	0·50	2·6	1·1	0·06
Cleveland, - -	3·4	1·10	1·3	0·4	0·03

In the early days of the basic process much difficulty was experienced from the variable content of silicon in different pig irons used, and to overcome this difficulty acid-lined converters were used in a preparatory process to remove the silicon before introducing the metal into the basic converter; this first blow lasted about five minutes.

The lining of the basic vessel is required to be strongly basic, and sufficiently refractory to withstand the very high temperatures to which it is subjected, without softening or melting. The materials generally applied for this purpose are lime, and burnt dolomite or magnesia, cemented and made plastic with tar, milk of lime, or other cementing material. In this country burnt dolomite mixed with a sufficient quantity of anhydrous tar is used. Dolomite, on heating to whiteness, contracts considerably, so that it is necessary to heat bricks made of this material to a high temperature before introducing them into the converter.

In Austria burnt lime and tar are used. The burnt lime is ground fine in a ball mill, moistened with water,

made into bricks, and burnt as hard as possible. These bricks are broken up, all the bad portions thrown out, and the good portions ground fine, mixed with about 15 per cent. of boiled tar, and stamped into the converter around the central core so as to form the basic lining. Such linings are said to stand 100 charges, but the twyers require frequent renewal.

In Germany dolomite and tar are mostly used for the basic lining. The burnt dolomite is ground to a certain degree of fineness, that which passes through a sieve of 0·2 inch mesh being considered the best size to use. A distinction is made between the material used for bricks and that used for bottoms. For the latter only freshly burnt dolomite is used, whilst for bricks old used portions are added. The dehydrated tar is mixed with the dolomite in a special mixer, about 12 per cent. being used for bricks, and 15 per cent. for bottoms. The bricks are first submitted to a pressure of 50 atmospheres in a powerful hydraulic press, and when this pressure is utilised as far as possible, another appliance is coupled on to give a pressure of 250 atmospheres. Separate twyers are often dispensed with, the basic material being rammed round pins, which are afterwards withdrawn, leaving holes for the introduction of the blast. These are less costly than separate twyers. The bottom stuff is stamped in either by power or by hand labour, the latter gives the best result and lasts longer. Sharpened pieces of wood are sometimes driven in to form the holes. The duration of a bottom depends on the compact and uniform manner in which the material has been rammed, and on the degree of drying to which it has been subjected. The number of twyer holes varies in different works.

The charging in of lime during the blow and the removal of the slag, formerly practised, is now generally abandoned.

The thickness of the bottom is about 2 feet. The life of a bottom averages about 20 heats. The loss of metal during a blow varies from 12 to 15 per cent., 8 to 9 per cent. of this being due to the silicon, manganese, phosphorus, sulphur, and carbon eliminated from the metal, the remainder is due to loss of iron. With low silicon, about 0·5 per cent., the loss is less. The phosphorus must be kept within certain limits, and should be from 1·7 to 2·2 per cent. Manganese should be present to the extent of at least 0·6, with a maximum of 1·5 per cent.

The concentric converter has been much used in connection with the basic process. The vessel being constructed in three separate parts, the neck is lined separately, and the body is lined in the usual way, round a central plug or core of cast iron. During the working the bottom gradually wears away, but it must not be allowed to wear more than 3 or 4 inches before repairing. The converter having been suitably lined and gradually heated up, a quantity of well-burnt lime is added, and, when strongly heated, the metal is run in from the cupola or from a ladle, the blast turned on, and the vessel rotated into the vertical position. The blow is marked by much the same phenomena as in the acid blow—pale flame and sparks during the combustion of the silicon and manganese, an increasing white flame, and then the drop due to the disappearance of carbon. There is no distinct change to mark the end of the blow. After the carbon is removed, a special feature of the basic process is the "after-blow" to oxidise the remainder of the phosphorus and sulphur. F. E. Thompson[1] states that the fundamental principle is to calculate the amount of air and lime required, and bring them into the bath. The only regular additions during the after-blow are lime, scrap, and recarburiser. Scrap and lime assist in cooling the bath, and the latter

[1] *Iron Age*, vol. 56, pp. 1260 and 1318.

thickens the slag. The blow lasts about 20 minutes. Formerly it was customary to take ladle tests, but now the judgment of the operator is often relied upon. With excess of lime there is more complete elimination of phosphorus and sulphur, but more oxide of iron goes into the slag. Without excess of lime some phosphorus returns into the metal, and is accompanied by oxide of iron, whilst the slag is "wild" and thin. Much phosphorus makes the steel cold-short, and causes a characteristic glitter in the fractured surface.

The temperature problem is the most serious one with which the operator has to deal. In addition to the variable temperature of the acid process, he has the lime addition and the after-blow to consider, and there are none of the accurate indications of the heat. But accurate reading is not absolutely essential, and scrap additions may be made. Possibly this lack of sensitiveness is due to the large amount of heat stored in the slag, whilst in the acid process there is chiefly only the heat of the metal to be taken into account. According to Mr. Thompson's experience, if not more than 10 per cent. of scrap is put into the converter the metal is uniform both in temperature and composition, and many successive blows will follow the same routine. Cold blows generally result from excess of lime or scrap, but may be due to lack of combustibles in the iron, such as phosphorus, or to low blast pressure. Hot blows occur when the combustibles in the iron are too high. Phosphorus towards the end of the blow does not readily pass into the slag, and scrap must be added. When lime is in excess in very hot blows, low phosphorus steel is produced with high conversion loss. Also the addition of too much scrap in hot blows is another cause of conversion loss.

With iron containing 2·5 per cent. of phosphorus about half is removed in the fore-blow. In hot or long fore-blows

more is removed, and in short ones less. The phosphorus reaction depends on the melting of the lime, and when this occurs phosphorus begins to be oxidised whether carbon is present or not Sulphur is more fixed than other elements. In a normal blow about half may be removed by manganiferous slags, and much more by after blowing. If sulphur exceeds 0·1 per cent. 50 to 90 per cent. may be eliminated. Rephosphorisation may occur if lime is deficient. Some analyses at the conclusion of the blow and before the addition of the recarburiser are as follows:

Carbon.	Silicon.	Sulphur	Phosphorus.	Manganese.
0·03	—	0·06	0·04	0·06
0·04	—	0·03	0·03	0·05
0·04	—	0·05	0·02	0·12
0·04	—	0·04	0·025	0·032

Analyses of various slags are as follows:

	I.	II.	III.	IV.
Silica, - - -	5·12	6·1	6·8	8·1
Ferrous oxide, -	17·85	17·5	19·9	19·7
Manganese oxide, -	3·80	3·9	4·2	4·0
Lime, - - -	50·00	49·0	48·5	47·3
Phosphoric oxide, -	20·30	20·0	17·0	17·5
Magnesia, - -	1·20	1·0	0·7	0·5
Alumina, - -	1·40	2·1	2·4	2·5
Sulphur, - - -	0·33	0·3	0·4	0·4

With less lime the phosphorus in the slag is decreased; oxide of iron is increased by an overblow, and by a cold blow; manganese depends on that present in the iron; silica depends on that in the iron and that introduced with the lime; magnesia is increased by the use of dolomite rich in magnesia as a lining or flux. A thick slag promotes the reaction between lime and phosphorus, but retards

mechanical intermixture. Very fluid slag retards dephosphorisation, but promotes desulphurisation of the iron. A sticky, highly basic slag is aimed at, so that it may mix readily and yet be sufficiently cool.

Formerly it was the universal custom to take samples for testing before adding the manganese compound. The converter was turned down and a ladle full of steel taken from it; this was cast into a small ingot, then hammered out flat, cooled in water, and the quality determined by the character of the fractured surface, as well as its degree of malleability and ductility. If the first sample was brittle, with an open crystalline grain, the vessel was turned up again, the after-blow continued for another minute or so, and again tested by means of a second sample, and so on until the required degree of malleability and toughness had been obtained. The recarburiser was then added and the metal run into the ladle.

The percentages of iron found in basic slag are variable, but Brevet[1] found that the slag with the least amount of iron came from the most satisfactory blow, and the metal was of the most satisfactory quality. The character of the blow, to a great extent, depends on the composition of the iron, and with uniform qualities of pig iron uniform blows can be obtained. The quantity of manganese is of special importance in connection with the heat of the blow, for if the manganese is too high it is necessary to continue the after-blow for a longer period in order to reduce the phosphorus to the desired minimum. Perhaps the best quantity of manganese to have present is from 0·6 to 0·8 per cent. It is a mistake to continue the after-blow too long, as this leads to a large amount of oxide of iron passing into the slag, and induces the conditions that result from a rephosphorising of the metal from the slag during the recarburising

[1] *Stahl und Eisen*, vol. xvi., p. 50.

period, so that the customary endeavour to insure complete elimination of the phosphorus may produce the opposite result. It seems therefore best to blow in such a way as to obtain a slag as low as possible in oxide of iron, in order to prevent the reduction of phosphorus during recarburisation.

The loss of metal during a basic blow is from 13 to 17 per cent., and with unsuitable pig iron may be much greater. This loss arises from the elimination of foreign elements in the pig iron, the loss of iron during the oxidation of these elements, and the mechanical loss of metal during the blow. With regard to the first, the lowest permissible amount of phosphorus should be 1·9, of silicon 0·2 per cent., and the total non-preventible loss about 7 to 9 per cent. The second source of loss depends on the temperature of the blow, and the relative basicity of the slag. The amount of iron in basic slag may be as low as 7, and as high as 15 per cent. This loss of iron is due to the after-blow, and varies with the quantity of slag produced. The mechanical loss of iron depends on the size and shape of the converter, and the quality of the pig iron used. A large converter diminishes the amount of loss of metal by particles thrown out, but a proper chemical composition is the best means of avoiding loss. A mixer therefore seems essential when "direct" metal is used.

Basic-Bessemer slag is now largely used as a manure on account of its phosphoric acid. The slag is first ground fine and sorted by machinery into various grades. It is found that hard slags, which contain more oxide of iron than soft slags, are preferable for manuring purposes. This is ascribed to the decomposition of calcium ferrate in soft slags, which have cooled slowly. In Germany it has been generally agreed that basic slags shall be sold according to the percentage of phosphoric acid, soluble in citrate solution. Citric acid solution readily dissolves out the

greater portion of the phosphoric acid in the slag, and is used as a guide to the amount of soluble phosphates present. It seems to be present as a tetrabasic phosphate, or it may be the ordinary tricalcic phosphate with lime, and probably the insoluble portion of the phosphates may be due to the presence of iron and aluminium phosphates.

Spectroscope.—The use of the spectroscope as a guide in determining the progress of the Bessemer blow has afforded valuable information, and was at first somewhat largely used; but as the process became better known, and skilled workmen were trained to carry it out, their eyes became so accustomed to the slightest changes—that is, in the acid process—that they could determine the different periods without any external aid. On the Continent and in America, where the irons are less siliceous than ours, the determination of the phases of the blow is not so marked, and the instrument is still occasionally used. Prof. Hartley[1] has made an exhaustive examination of the subject, and makes the following statements from his observations:

"When the iron contains low manganese the latter is oxidised during the first few minutes, a portion of the combined carbon being oxidised at the same time. The graphite is converted into combined carbon. When the combined carbon begins to be oxidised the action increases rapidly. The silicon at the same time is rapidly oxidised until, during the finishing period, there is very little left. In the slag-forming stage, when the lines of the alkali metals are not visible in the spectrum, the carbon is all oxidised to the form of carbon dioxide; but as the temperature rises carbonic oxide is produced. At this period the lines of the alkali metals are seen, and during the boil the gases are those that produce a reducing atmosphere, and the com-

[1] *Jour. Iron and Steel Inst.*, No. 2, 1895.

bined carbon is oxidised to carbonic oxide. The temperature is now very high, and both iron and manganese are volatilised. Towards the end of the fining stage the manganese is reduced in quantity and the iron is increased. Suddenly the iron spectrum is enfeebled, and the blow is stopped. Without doubt we have now a rapid diminution in temperature, because the only combustible left is iron. The Bessemer flame is not due to combustible gases and vapours being mixed with oxygen and burning within the converter, but, on the contrary, it is carbonic oxide mixed with metallic vapours at an exceedingly high temperature burning outside the converter in cold air."

Le Chatelier has measured the temperatures of the blow in a Robert converter, and gives the temperature during the boil as 1330° C., and at the finish as 1580°. The temperature of the steel in the ladle is given as 1540°. The composition of the pig iron used, and the more or less rapid rate at which it is blown, undoubtedly influence the temperature. The greater the mass of material operated upon the greater will be the rise in temperature.

The appearance of the flame from the converter, when viewed through a spectroscope, varies at different stages of the blow. At first, when the flame is small, a faint continuous spectrum is observed. As the flame increases in volume two yellow lines appear, due to sodium. With a still brighter flame red and violet bands also appear. During the boil additional lines appear in the red, with carbon lines in the green and blue, and manganese lines also in the green. At the close of the boil the spectrum fades in intensity, and the carbon and manganese bands in the green disappear.

Gjers' Soaking-pits.—The object of these is to utilise the internal sensible heat, given out by the metal while cooling,

for the purpose of bringing the whole ingot to the proper temperature for rolling, without the necessity of reheating. The pits are square in section, and are built of masonry. The depth and height are a little greater than the size of the ingots to be placed in them. They are used for steel ingots obtained from the Bessemer and open-hearth processes. Soaking-pits are represented in *H*, Fig. 104, used in connection with a Bessemer plant. *A* is the converter, *B* the ladle, *C* the movable platform, *D* two of the ingot moulds, *E* the crane to remove the ingots from the moulds to the

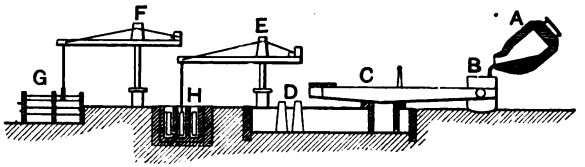


FIG. 104.

soaking-pits, *H* the brick soaking-pits, *F* the crane for lifting the ingots from the soaking-pits to the rolls *G*. The ingot of metal is removed from the mould as soon as it has sufficiently solidified, then placed in the hot pit, and closely covered. By this means the heat given out by the metal is absorbed and stored up by the brickwork. In about an hour the ingot will be at a uniform temperature throughout, and sufficiently hot for rolling. During the soaking process a quantity of gases is liberated from the metal, consisting of hydrogen, nitrogen, carbonic oxide, etc.; thus excluding the air, and preventing oxidation. If the brickwork becomes overheated, it may be cooled by dropping in some coal, when the surplus heat is absorbed in decomposing the coal and in volatilising the products. Considerable economy is claimed for this mode of working, as the loss of metal by oxidation during reheating, together with the requisite expenditure of fuel, is largely avoided.

Soaking-pits give the best results when the output is as large as possible. Daelen[1] says: "If the output is less than 300 tons per 24 hours, the intervals between the heats are so long, that the pits remaining unoccupied, lose too much heat to enable them to subsequently yield ingots of the customary temperature in ordinary work. In such cases it is usual to heat the pits by gas. To carry out this system a group of pits has to be arranged systematically with gas firing, each one being easily separated from the rest. This is difficult to arrange, and inconvenient in actual work. If heating is employed, then is there not only an increased consumption of fuel, but an increased loss of metal by scaling. The loss by oxidation during transport and rolling is about $\frac{1}{2}$ per cent. Subtracting this, the loss of metal by treatment in a reheating furnace amounts to about $2\frac{1}{2}$ per cent., in heated soaking-pits to $1\frac{1}{4}$ per cent., and in unheated pits to about $\frac{1}{2}$ per cent."

Daelen adopts a moveable soaking-pit on wheels. The ingot is placed on a fire-brick base, and over this is a hood, which is rapidly heated, so that the temperature is regular, and the oxidation less.

[1] *Stahl und Eisen*, vol. xvi., p. 61.

CHAPTER XXII.

OPEN-HEARTH PROCESS.

THIS is a process for the production of cast steel on the hearth of a regenerative gas furnace. Three modifications have been adopted. (1) Pig and scrap, or Martin process; (2) pig and ore, or Siemens process; (3) a combination of the two former, which is now generally adopted, and termed the Siemens-Martin process.

The first or Martin process consists of melting malleable iron with pig iron, preferably low in silicon and containing manganese. When the charge is melted it may be kept in fusion, because the intensity of the oxidising action may be easily maintained. In order to hasten the operation, the pig iron may be charged into the furnace in the liquid state and speedily raised to a white heat; the malleable iron, previously made red-hot, is then added in lumps. With a neutral flame, No. 1 grey pig will dissolve 9 times its weight of Bessemer scrap, while No. 3 pig will not dissolve more than four times its weight, and, when the flame is oxidising, considerably less. The oxide of iron Fe_3O_4, formed by oxidation, reacts on the carbon of the pig iron, producing carbonic oxide, which, on escaping, agitates the bath of metal, and thus tends to make it uniform in composition. When the whole is melted a test is taken, and when the metal

shows the proper fracture and toughness as well as the right degree of decarburisation by Eggertz' test, it is run into a ladle and cast into ingot moulds, as in the Bessemer process. This method of working is only possible with the best pig iron, so that the usual plan is to completely decarburise and then add spiegel-eisen, or ferro-manganese. The latter containing more manganese than the former, a less quantity is required for deoxidation, and, as therefore less carbon is added, a milder steel is produced.

The second or Siemens process is worked with pig iron and pure rich oxides, the latter replacing the scrap iron of the Martin process. In the latter the iron takes up carbon from the pig iron, but in the Siemens method the oxide of iron assists the atmosphere in its work of oxidation. It partly removes the silicon, manganese, and carbon, so that the process is hastened and the material used is less costly. The difficulty has been to make the light ore thoroughly penetrate the denser metal. This has been partly avoided by adding the ore in small portions at intervals. The weak point of this method is the corrosive action of the basic oxide on the lining of the furnace, forming an acid silicate of iron, which increases the amount of ore required, especially when a large portion is added at one charge. 8 to 12 per cent. of ferro-manganese or spiegel-eisen is added at the conclusion.

The third, or Siemens-Martin process, is similar to the Siemens process in the mode of working. Pig iron is first charged into the hot furnace, and then iron and steel scrap, in small quantities at a time, and a certain quantity of rich oxide of iron; spiegel-eisen or ferro-manganese is added as usual at the conclusion. In the above three modifications it is necessary that the pig iron employed should contain but little phosphorus and sulphur, as these elements are only removed to a moderate extent by the process, in consequence of the siliceous nature of the slag, which is but

feebly oxidising, so that phosphate of iron could have but a temporary existence.

The Siemens open-hearth furnace is of the reverberatory type, having a slightly concave bed lined with sand, which has been well rammed in and strongly heated. The bed also

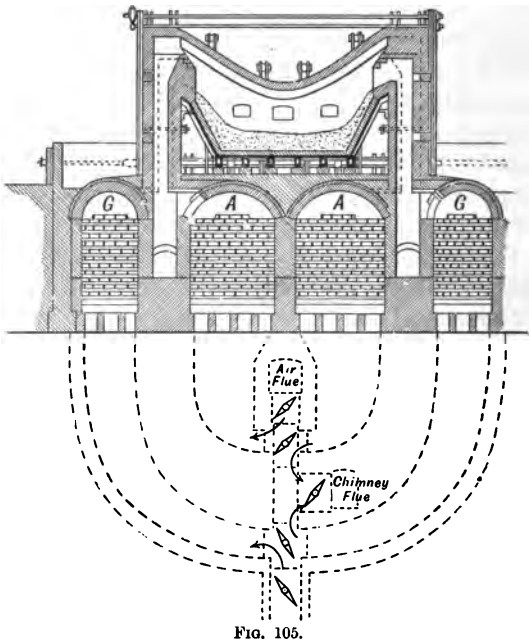


FIG. 105.

slightly inclines towards the tap hole, which is situated beneath the middle working door on the front side of the furnace. The roof is lined with silica brick. In a later form of this furnace (Figs. 105, 106) the roof has a strong slope from each side to the centre, giving a very plunging flame; the air space beneath the bed is enlarged, the gas ports are longer and narrower, and the regenerators are larger and roofed with semi-circular arches, so as to give a

larger exhaust flue for the flame, and thus modify its temperature before it reaches the regenerators. The furnace has three doors, the outer ones being used for charging and the middle one for working. The dotted lines below the furnace indicate the valve arrangement and the flues, through which the gas and air pass to the pairs of regenerators alternately. It will be noted that the air regenerators are larger than those used for the gas. The reversing valves are simple

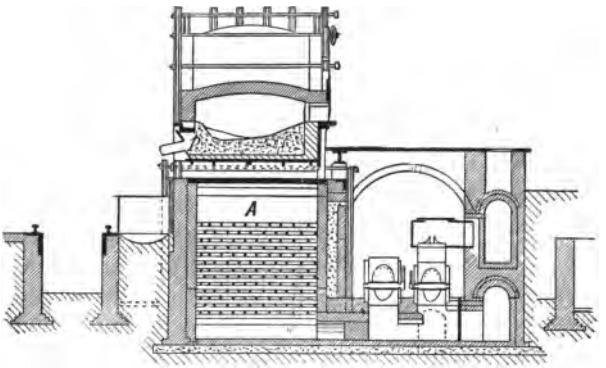


FIG 106.

flaps acting like a four-way cock, and actuated by means of levers. The more modern furnace is of much greater capacity than the early one, 10 to 20 tons being now often treated in one charge.

Considerable difficulty was experienced at first to find a suitable material to resist the high temperatures attained in this furnace, as the ordinary Dinas brick, although very refractory for most furnaces, was rapidly melted. A brick specially prepared by crushing pure quartz rock, and mixing it with 2 per cent. of quick lime to give it cohesion, answers well The hearth is made of white sand, with a small admixture of more fusible fine sand, which mixture sets exceedingly hard at a steel melting temperature, and possesses the

advantage of combining into a solid mass. Fresh materials are introduced between the charges to make up for wear and tear. The furnace roof, made of the above-mentioned materials, is very little attacked when the Martin process is used, although the heat is sufficient to maintain iron, with only a trace of carbon, in a perfectly fluid condition. The use of raw ore entails the disadvantage of a much more rapid destruction of the furnace lining, and even the purest magnetic oxide necessitates the addition of raw lime for the formation of fusible slag with the silica of the pig iron and of the furnace lining, and the dust arising from the lime and ore also causes the silica bricks to corrode somewhat rapidly.

It is evident then that silica bricks are objectionable in the construction of the hearths of open-hearth furnaces, because they prevent the formation of basic slags. Siemens tried bauxite as a basic lining for the furnace bottom, but failed, owing to the great contraction of the mass when intensely heated, and non-cohesion with the same material introduced for the purpose of repairs. When an attempt was made to replace the silica bricks of the sides and roof by bauxite bricks, these were not found to be equal in heat-resisting power to silica bricks.

If good hematite pig iron is employed in the open-hearth a metal of high quality results, being only inferior to the best Swedish cast steel. The process resembles the Bessemer process, in that both produce steel by the decarburisation of pig iron, yet there are important differences in the nature of the chemical changes and in the quality of steel produced. In the Bessemer process, the silicon and carbon are fully oxidised by the action of the blast, while sulphur and phosphorus remain unoxidised. Manganese is oxidised only to a limited extent, and therefore it is not necessary to add spiegel-eisen at the end of the operation,

when the pig iron employed contains a moderate amount of manganese, as is the case with Swedish and Styrian iron. Mr. A. Willis, of Landore Steel Works, found Bessemer steel, made without addition of spiegel, to contain as much as 0·3 per cent. manganese. Notwithstanding the non-oxidation of this manganese, from 8 to 10 per cent. of iron is oxidised in the Bessemer process. This oxidation of iron is an advantage in so far as it produces the necessary amount of heat to keep liquid the resulting iron, which would otherwise solidify in the converter. In the open-hearth process, when ore is used, a totally different result ensues, as is shown by the following experiment by Siemens: A manganiferous pig was melted and ore charged in the usual manner. The silicon and manganese were oxidised first, and then very little change took place in the carbon until the phosphorus and sulphur had been largely removed. This enables pig iron to be used that contains small amounts of these impurities. The decarburising agent employed being ferric oxide, the metalloids are oxidised, and occluded oxygen does not appear to exist in open-hearth metal to anything like the extent it does in pneumatic metal, but the addition of spiegel or ferro-manganese at the conclusion is generally an absolute necessity. The reason of the different reactions in the Bessemer process is, according to Siemens,[1] "that the silica liberated at the beginning of the operation requires a base for its saturation, and that its great affinity for protoxide of iron determines the oxidation of this metal (free oxygen from the blast being present) in preference to manganese."

A characteristic difference between the two metals, in their fluid condition, is, that Bessemer metal, on cooling in the moulds, sets up a violent ebullition, probably resulting from the reaction between occluded oxygen and carbon,

[1] *Jour. Iron and Steel Inst.*, 1873.

which is counteracted by stoppering the moulds. The open-hearth metal, if it has been made with care, contains but little occluded oxygen, and sinks in the moulds on cooling in the same way as dead-melted steel from the old Sheffield process.

With respect to the notion of Sir William Siemens, that manganese has a different affinity for oxygen in the open-hearth from that in the Bessemer process, there are many reasons to doubt this statement, and probably, with pigs containing the same quantity of manganese, oxidation would be as effective in one as in the other process. There can be no question as to the value of manganese in removing oxygen from metal produced in both processes, and while this is its chief function, it also acts very beneficially when a certain portion is left in the steel. If too small a quantity of manganese is added to the metal it is red-short and difficult to roll, so that it is generally necessary to add such a quantity as to ensure at least 0·25 per cent. remaining in the metal. Now if it be assumed that this portion forms an alloy with the steel, such an alloy appears to prevent red-shortness. It probably acts in promoting the solubility of the sulphur and such elements as tend to make steel brittle.

Now during the melting stage carbon, silicon, and manganese are partly oxidised, varying with the temperature, but when the metal is fluid the carbon remains almost stationary, until practically the whole of the silicon and manganese is oxidised, which takes 3 to 4 hours. During this stage, no gas being given off, the bath of metal remains tranquil. When the silicon and manganese have been practically oxidised the carbon begins to oxidise, forming carbonic oxide, the evolution of which gives an appearance of boiling. This continues until the carbon is reduced to 0·1 per cent. or less, when the metal again becomes tranquil,

and the brown slag changes to black, due to absorption of oxide of iron.

The pig iron most suitable for the open-hearth process—the sulphur and phosphorus being low—is that containing the least carbon and silicon. In the first place it contains a higher percentage of iron, and in the second place it does not require to be so long in the furnace before the iron is completely decarburised. Moreover, highly siliceous pigs generally yield inferior steel. More than 0·5 per cent. of manganese is objectionable, not only because it causes delay, but because of the action of oxide of manganese on the silica lining. No metal added to the charge seems to have the power of eliminating sulphur, but manganese is the most important in counteracting its influence, and that metal is indispensable in all steel made by an oxidising process. The open-hearth process is valuable for making soft steel, as it eliminates silicon, and the carbon in the finished metal can be completely controlled.

In the year 1884 Mr. Frederick Siemens introduced a new shape of regenerative furnace, in which the principle of a slanting roof was abandoned, and the roof raised so as to incline upwards instead of downwards. The object of this arrangement is to prevent the flame coming in contact with the metal, the heat only being radiated on to it. The gas and air ports are placed somewhat near the roof, and at some distance from the side walls, so that the gas and air after ignition may have unobstructed space for entering into combustion and for free development of flame, which also passes above the working doors. The furnace is necessarily high and wide, as heating by radiation requires a large space for development of flame.

Mr. Siemens states from his own observation that a reheating furnace, using solid fuel, requires three tons of coal in a shift of ten hours, while a regenerative furnace of

equal capacity only requires two tons. In the latter furnace a very high temperature is obtained, and by the radiation method of heating it is claimed that a great economy of fuel is effected, as well as an increased life of the furnace, because the active flame does not act on particles of solid matter, which interrupt the process of combustion and produce smoke. A short combustion chamber always gives unsatisfactory results, because the flame is hardly formed before it has to pass through the outlet ports into the regenerators, where the combustion is checked, and smoke results as a consequence. Therefore in the regenerative gas furnace of the radiative type the heat of the flame is utilised in two distinct periods: The radiation period, with its active combustion of the highest intensity, which is largely confined to the furnace chamber; and the absorption of the waste heat by the brickwork of the regenerative chambers.

In 1876 Pernot introduced his open-hearth regenerative furnace, with a revolving bed, inclined at an angle of 5° or 6° to the horizontal. Pig iron, previously heated to redness, is placed on the bed of the furnace and covered with scrap iron. The bed of the furnace is then made to revolve slowly, the pig iron gradually melts, and the scrap is alternately exposed by the motion of the furnace to the strong heat of the flame, and immersed in the molten pig iron. In this way the fusion is comparatively rapid, the whole mass becoming fluid in about two hours. The process is completed in the usual way. The furnace is indicated in Fig. 64. When repairs are necessary, the bed on its carriage is drawn out. In practice it is found that these furnaces require frequent repairing. With a view to making this easier, Pernot arranged a movable roof, which has besides the additional advantage of somewhat reducing the strain on the structure occasioned by great variations in temperature. The furnace has not been adopted in this

country, and has made but little headway in France or America. There is no doubt that a charge can be worked off quicker than in the ordinary Siemens furnace, and consequently, in addition to saving time and labour, there is also a saving in fuel. In working, however, at such high temperatures there are mechanical difficulties opposed, even to the simplest construction of furnace holding together, and these difficulties are enormously increased in dealing with a complicated furnace such as that of Pernot. It is claimed for the method that with a 5 ton charge, 5

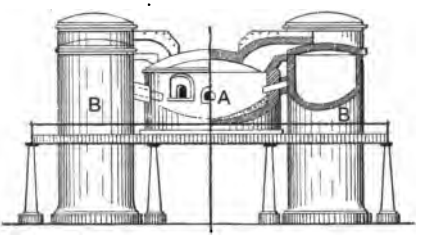


FIG. 107.

operations may be completed in 24 hours, each charge requiring 7 cwts. of coal, and 1½ cwts. for the preliminary heating of the pig iron.

In 1884 Messrs. Riley & Dick brought to the notice of the Iron and Steel Institute a new form of regenerative furnace, in which considerable departures were made from previous practice of furnace building. The principle is the same as that of the open-hearth, but it is designed to decrease the cost of construction and maintenance.

The furnace or melting chamber (A) (Fig. 107) consists of a circular or oval body with an iron or steel casing. It is placed on a platform, supported by girders, and left entirely clear underneath, so that the bottom is kept cool and the lining better preserved. The four regenerators (BB) form four circular towers, and instead of being

situated below the bed of the furnace, are placed in pairs at opposite ends of the furnace; each regenerator forms a separate structure, which is out of harm's way in case of the metal breaking out, and as it has only its own weight to carry it cannot get out of shape. It is very desirable to regulate the relative amounts of the heated gases passing through the regenerators, in order to control the relative amounts of heat stored up in these chambers. The tendency is for the gas-chamber to receive the largest share of the waste heat, whereas the air-chamber should be the more highly heated of the two. The regulation is effected by the adoption of a new kind of disc-valves.

The regenerators are 6 ft. 6 in. internal diameter, lined with 9 in. firebrick, and have outside casings of $\frac{3}{16}$th inch steel plates. The Batho method of arranging the flues has been adopted, the distinctive points of which are: that the gas and air ways are brought up outside the furnace, instead of inside as is the case in the Siemens furnace. In the latter form the expansion and contraction disturbs the brickwork, causing cracking, which leads to a mixing of the gas and air before entering the furnace ports. In the Batho type the external arrangement of the flues simplifies the furnace itself, reducing it to a simple box, which may be readily lined by ramming or by brickwork. The ports are of the Hackney type, the air port being placed vertically, or nearly so, above the gas port, so that the two streams directly unite and are not deflected, as in the Siemens type.

The roof is dome-shaped, as in Siemens radiative furnace, but is not used for the purpose of radiating the heat of the flame, as the flame is thrown directly down upon the material to be heated. The roof may be made movable so as to introduce large pieces of scrap.

This class of furnace is worked with a basic lining for the

bed and a lining of silica bricks for the roof, which is suspended from girders so as not to rest on the sides of the hearth, a space of about a quarter of an inch being left between the basic and the acid linings.

In 1887 Mr. J. W. Wailes[1] introduced the Batho furnace, with a view to basic working. It consists of separate parts, taking the form of independent regenerators and combustion chamber, or melting vessel, the two being connected by tubes. The leading idea is to get the melting chamber into as compact and manageable a form as possible. The advantage claimed for separate regenerative chambers is to avoid the inconveniences arising from expansion and contraction; to secure simplicity of construction, as distinguished from furnaces where the regenerative chambers are included in the same block of brickwork; and to afford the greatest possible facilities for cleaning and changing the internal brickwork.

The roof is carried independently of the sides, and the latter can be removed without disturbing the roof. The sides, up to the top of the door and gas-port, are of basic material. The upper part, about 1 ft. 6 in. in depth, is of silica brick, and is made in sections held in frames. The natural slope of the sides will allow repairs to be made by simply putting basic lining material on the slope from the outside. For the 12-ton furnace, about 3000 basic bricks are required. For the movable sections, with that part over the gas-port and doorway, 2000 ordinary silica bricks, and for the lid about 3000 more; making for the upper lining of the vessel 5000 silica bricks. A total weight of basic material amounting to 15 tons is used. The acid sections do not rest on the basic lining. The joint between the lid and the upper part of the sections can be easily made with siliceous clay; that between the

[1] *Jour. Iron and Steel Inst.*, No. 2, 1887.

sections and the basic lining with a little lime mixed with tar. Basic and acid material may come together without difficulty, provided that the one does not rest or impose weight on the other. If, however, the contact is maintained by pressure, rapid fusion takes place.

The basic lining is of burnt dolomite and tar, as in the case of the basic Bessemer process. For that part above the slag line, however, an addition of 10 per cent. of silica sand may be used with advantage. The silica part of the furnace lining is built in first and then dried, then the basic portion, in the form of bricks 11 in. × 4½ in. × 3 in. These bricks are produced by hydraulic pressure, equal to 150 tons on the 11 in. bricks. They are conveyed at once to the furnace and fixed, and as soon as the lining is complete the gas may be turned on. When the hearth is red hot the metal may be charged in, and in this particular the basic-lined furnace has a great advantage over the acid-lined one, the hearth of which requires several days to be fused in.

In a basic hearth a basic slag must always be present, and the purifying agent must be created as early as possible in the working of the charge. It is of course important to keep the bottom in repair, and this may be done by placing dolomite on the sides of the hearth, and allowing it to run down to the bottom. Mr. Wailes claims that the basic open-hearth possesses advantages over the acid open-hearth in the production of mild steel.

Mr. F. W. Harbord conducted a number of experiments in the above furnace to ascertain the manner of removal of the metalloids. The *modus operandi* was to take samples at intervals of half an hour from different parts of the bath. In each cast the charge consisted of 60 per cent. pig, 30 per cent. steel scrap, and 3 per cent. spiegel. The composition of the bath being: Carbon, 2·3; silicon, 0·87; phosphorus, 2·3;

sulphur, 0·23; and manganese, 0·96 per cent. He found that the removal of the impurities was in proportion to the oxidising nature of the slag present. The silicon and manganese are largely oxidised during the melting down stage, about 40 per cent. of the sulphur and phosphorus, and from 30 to 80 per cent. of the carbon, according to the intensity of the oxidising influences present. Now as the process proceeds the slag takes up more ferrous oxide, but if a highly basic slag were present during the melting stage practically the whole of the metalloids might be removed, with perhaps the exception of sulphur.[1] Harbord states that nearly the whole of the iron in the slag is present in the form of protoxide. Whether it oxidises the impurities by giving up its oxygen and being reduced to the metallic stage, or whether part of the protoxide is oxidised by the atmosphere of the furnace into magnetic oxide, and is again reduced to protoxide—so acting as carrier of oxygen of the air—is an open question; probably both these reactions occur.

Sir Lothian Bell mentions a case wherein he removed 98 per cent. of the silicon; 45 per cent. of the sulphur; and 44 per cent. of the phosphorus, by passing molten iron through melted oxide of iron. This is exactly what is done in the basic Siemens furnace, only that the time of contact being longer, and the basic conditions more perfect, the impurities are more completely eliminated. In a puddling furnace, as the charge is melted, it runs down into the hearth, and is actually puddled in a bath of molten oxide, while the other part of the charge is melting. The difference between this and the open-hearth is, that instead of depending on the puddler's rabble for intimate admixture, the temperature is maintained sufficiently high to keep both slag and metal in a state of fluidity, and thus to ensure thorough uniformity. Although it may not be possible to regulate

[1] *Jour. Iron and Steel Inst.*, No. 2, 1886.

the slag so as to ensure a constant result, there is no difficulty in oxidising the silicon and manganese during the melting period.

It will be seen from the above that makers of dead mild open-hearth steels are seldom troubled with high silicon, but in the manufacture of steels with varying carbons, occasional heats with undue amounts of silicon do occur. If a bath of steel is worked in the usual way, that is to say, if the ore is added after the bath has been melted, at regular intervals, any desired carbon, with low silicon, can be obtained, but if the ore is added with long intervals between, the slag thickens, and the bath gets very hot, with the result that silicon is reduced from the slag and passes into the metal.

M'William & Hatfield[1] have studied the elimination of silicon in the acid open-hearth, and question the opinion that the occasional high silicons are due to a "sand-boil," or to a special attack on the bottom or banks of the furnace, whereby the silica is reduced to silicon and transferred to the steel. Experiments were made in a furnace with the bottom and banks in bad condition; and also with the bottom and banks in good condition; but the silicon seemed independent of these variations. When the slags came to be examined it was found that the elimination of the silicon was intimately related to the character of the slag. In those heats finishing with thin slags the steel was low in silicon, and in those with thick slags the silicon was correspondingly high. This means that thin slags are more basic than thick ones. The fluidity of the slag is not in itself the cause of the more complete separation of the silicon from the iron, but the degree of basicity, which causes the slag to be more fluid as it becomes more basic. With a very acid slag a temperature is reached at which silica is decomposed and at which

[1] *Jour. Iron and Steel Inst.*, No. 1, 1902.

silicon cannot unite with oxygen, therefore it goes into the iron. The result of these experiments seems to be that the removal or otherwise of silicon from iron depends on the composition of the slag and on the temperature.

One of the chief defects of the original open-hearth furnace was that a large portion of the superincumbent weight of the furnace and its charge was supported by the brick walls between the gas and the air regenerators, which at the upper part were softened by the intense heat on both sides. This fault is now generally corrected by encasing the hearth in plates of iron. This iron shell is carried on iron beams extending across the furnace, and resting on exterior walls or columns, which are independent of the more highly heated and perishable parts of the furnace below.

Natural gas has been largely used in favoured localities for the open-hearth. In America it is carried to the furnace through 3 in. pipes, which branch off to both ends of the furnace through 2 in. pipes. The delivery and reversing of the gas is regulated by ordinary globe gas valves placed in the circuit. This gas is not diluted with a large proportion of nitrogen, as in producer gas. Natural gas is not generally pre-heated, as this tends to decompose it, and fill the chequer-work with deposited carbon. The furnaces are built with two regenerators at each end of the furnace and connected with the air inlet-valve, while some are built with only one regenerator at each end of the furnace for heating the air. In this case the air valve and air regenerators are built larger, with 60 per cent. greater capacity than when using producer gas. Low pressure is employed for the gas.

The tendency in America in the eighties was to increase the size and capacity of open-hearth furnaces, and furnaces of 30 to 40 tons capacity began to be erected, instead of the usual 7 or 8 ton furnaces. The Lash open-hearth

furnace, with the use of natural gas, may have a capacity of 40 tons. The hearth is elliptical and of the Batho type, similar to that of Mr. Dick. The furnace has two doors, which are placed at the end of the same diameter, at right angles to the direction of the flame. The working doors can be arranged symmetrically, on a semi-circumference, between the two front regenerators, the tap-hole being placed in the middle of the other semi-circumference.[1] When producer gas is used, the air regenerators are larger than those for the gas, since air is generally introduced at the same temperature as that of the gas coming from the producers. It is well known that the gas regenerators are, in ordinary working, more highly heated than those for the air, which causes an unequal heating of the mixture, thus impeding the combustion. This furnace obviates this difficulty by allowing the escaping gases to pass through the regenerators in variable proportions. The inconveniences of the ordinary open-hearth may be enumerated as follows:

1. The depth of the excavations caused by the regenerators being placed below the base of the furnace and underground.

2. The want of solidity in the construction of the furnace, which, when the base of the furnace rests on the walls of the regenerators, is often loaded with over 15 tons.

3. The danger of overflowing and loss of metal from the hearth by fissures in the masonry.

4. The great outlay caused by the excavations and masonry below ground.

5. The inconvenience to the workmen, who are obliged to stand on metal plates heated by the regenerators below.

[1] *Trans. Amer. Inst. Mining Engineers*, Vol. xvi., p. 693.

Among the advantages of having the regenerators above ground, isolated from the furnace, and enclosed in iron casings, are:

1. Easy access to the different parts, and simplification in repairs.

2. The regenerators and the gas and air passages being entirely separate, accidental combustion of the gas, due to leakage, is avoided.

In 1889 Mr. J. H. Darby of Brymbo communicated to the Iron and Steel Institute the particulars of his new 20-ton open-hearth furnace. The furnaces are built in a line, the charging platform on one side being a sufficient distance from the floor of the works to admit the casting ladle and carriage, which runs on rails over a pit parallel to the furnaces. Each furnace is provided with a chimney, ordinary butterfly valves of ample size, and regenerative chambers of large capacity.

The furnace is composed of two wrought-iron sides, supported by H iron buck-staves, well braced together at top and bottom. The plates are cut away for the working doors, and also cut away to allow of air circulation under the furnace bottom and bridge plates. The bottom is built of cast-iron plates, supported on girders, which rest on angle iron attached to the side plates. The silica blocks at each end are built in the usual manner, but the roof and side walls are built after the hearth has been rammed in. The roof is level from block to block, but the ends are well inclined, to bring the flame down on to the metal. The iron plates for the bed are first lined with fire-bricks, and on these is placed hard, burnt dolomite, mixed with a little tar, and rammed to the desired shape with hot iron tools. The tap hole is made with a round piece of wood, which is burnt out as the furnace becomes hot. On the prepared bed of dolomite is a layer of about two inches of chrome iron ore,

ground fine, and mixed with tar. Chrome iron ore is also rammed in between the silica blocks and the basic hearth. The side walls and jambs are built on the chrome ore. The roof is then put on, and the furnace gradually heated up.

80 per cent. pig iron and 20 per cent. scrap is used. When this is melted, iron ore and limestone are added at intervals during about five hours. When the decarburisa-

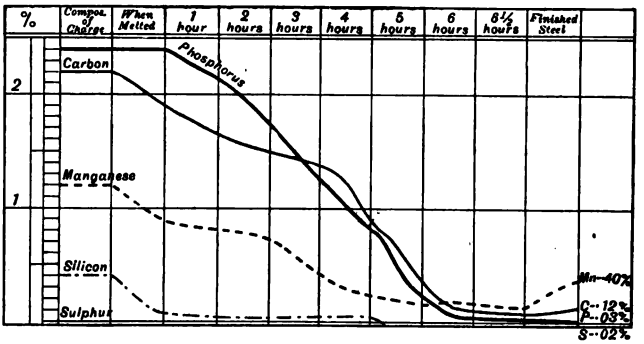


FIG. 108.

tion is finished 10 to 12 lbs. of ferro-manganese per ton of iron are added. Dephosphorisation is practically complete. The diagram (Fig. 108) shows the order in which the various impurities are eliminated. An average analysis of the soft steel made is as follows: Carbon, 0·12; phosphorus, 0·03; sulphur, 0·018; and manganese, 0·40 per cent. Such steel gives a tensile strength of 24·5 tons per square inch, with an elongation of 31 per cent. in 8 inches.

Kjellberg[1] discusses the result of his investigations of the open-hearth furnaces of Germany, Austria-Hungary, and France. In no works that he visited did he find either dolomite or lime used exclusively for basic linings; neither is chrome iron ore used alone for this purpose. Frequently a

[1] *Jernkon. Annaler*, Vol. xliv., pp. 389-466, No. 7.

mixture of lime and dolomite, with magnesite, was used, and sometimes a mixture of chrome iron ore and magnesite, with or without lime. Sometimes basic bricks were used, but generally basic material stamped in. Whether lime, dolomite, or magnesite is used, it is first calcined sweet, broken down, then ground and mixed with binding material. Magnesite, unlike dolomite and lime, may remain exposed to the air for an indefinite time without undergoing deterioration. In making dolomite bricks boiled tar is generally employed as the binding material, although burnt or unburnt dolomite and water have been used for the purpose. At Dios-györ Works in Hungary no tar is used, but the finely sifted dolomite is made plastic by mixing with milk of dolomite, made by mixing partly calcined dolomite with water. Or milk of lime may be used In most works the hearth is constructed partly of dolomite and lime stamping, and partly of magnesite bricks, a stamped bed resting on a brick underlay, lasting much longer than when the bed is made wholly of stamped material. In order to save cost, the lowest layer is made of acid bricks, and on these are placed the magnesite bricks, then the dolomite stamping. When the stamping is wholly of magnesite it is unnecessary to have basic bricks as a foundation.

The fire-bridge is always made of basic material. In most cases it consists of a core of magnesite bricks resting on the cooling plate, against which the hearth is stamped. When dolomite or lime is the basic material used it must be kept from contact with the acid roof by an intervening layer of magnesite or chrome iron ore, which should be 1 to 2 inches thick. The walls are always made of basic material up to a height above the point at which the boiling slag may reach when the hearth is full. The tap-hole is formed with magnesite bricks. As a mortar, powdered and sifted

magnesite is used, together with tar, or milk of dolomite or lime, or with water alone. The tap-hole is closed with similar material.

Recarburisation of Iron.—In the early days of the Bessemer process attempts were made to recarburise iron in the converter by the addition of charcoal, but it was not then known that at high temperatures carbon is harder to oxidise than manganese and silicon, and unless oxygen is first removed the steel is useless. It was then found that grey pig iron with high silicon could be used as a deoxidiser, but too much silicon was apt to remain in the metal. Gaseous and liquid carburising materials were also unsuccessfully tried, and only manganese compounds were found to be successful. If powdered charcoal was blown in with the blast the only effect was to raise the temperature without materially affecting the iron. The manganese compounds have continued to be used to the present time. But spiegel-eisen and ferro-manganese are far from pure substances, and introduce impurities into the iron. When the microscope began to be practically used in the examination of metals it was found that the manganese did not alloy so readily with the iron as had been assumed, and if not thoroughly well mixed with the iron it showed a tendency to segregate. This explained many mysteries in the curious fractures of steel, and the additions of manganese were reduced to the quantity required for deoxidation. The basic Bessemer process especially led to a product comparatively rich in oxygen, on account of the after-blow, therefore a larger quantity of manganese was required to remove it, and this high manganese prevented the production of high carbon steel unless much manganese was also left in the steel. Efforts were therefore made to recarburise the iron without the addition of so much manganese alloy. If the deoxidation was effected in

part by spiegel-eisen and completed by the addition of aluminium, only mild steel could be produced. Darby then introduced the use of free carbon for this purpose. In adding the carbon there is no marked change in the other elements, and as the carbon is added to the charge in the ladle, there is no reduction of phosphorus from the slag.

Darby Process of Recarburisation.—It is well known that in the basic process, either Bessemer or open-hearth, it is easy to decarburise pig iron, and to make from it mild steel, but very difficult to make steel with a regular percentage of carbon above 0·5 per cent. The Darby process aims at overcoming this difficulty, and produces steel with 0·15 to 1·0 per cent. of carbon at will. As the process deals with the metal after the furnace operation it is applicable both to the Bessemer and open-hearth processes. Now in these methods of making steel it is necessary to add a manganese compound to take up the absorbed oxygen, and as in the basic process the phosphorus is passed into the slag, anything in the nature of a reducing agent added to the bath of metal containing slag will tend to reduce the phosphorus from the slag, which then passes back again into the iron. This action becomes more effective the longer the reducing agent is allowed to remain in the molten bath. Now even if one succeeded in removing part of the oxide of phosphorus by pouring off the slag and regulating the amount left in the bath, the production of low phosphorous steel, high in carbon, would be difficult. It was first thought to recarburise the iron by means of carburetted gases, and by tar, petroleum, and similar substances, without any satisfactory result. Mr. John Darby then devised the method of pouring the iron through a tube perforated at the bottom, and containing carbon, from which the carburised iron ran into the ladle. It was found that the absorption of carbon by the iron was so rapid that

the lengthened time required by the above method of filtration was unnecessary. The next plan was to run into the filter vessel a stream of carbon particles at the same time as the metal was teemed into it. It was found that sufficient carburisation occurred during the teeming of the first third of the charge. The employment of the carburising vessel was afterwards found to be unnecessary, and now in similar processes it is customary to throw into the ladle at intervals a definite quantity of finely divided carbon. By this means a considerable economy is effected, due to the saving of spiegel or ferro-manganese. In some American works dry crushed coke, in paper bags, each holding about 50 lbs., is thrown into the ladle along with the decarburised metal from the open-hearth, the first bag being thrown in as soon as the bottom of the ladle is covered with metal. The accuracy of the method may be understood when it is stated that, out of twenty-four cases the desired carbon only varied by 0·02 per cent. About half the carbon added is taken up by the iron.

Chemical Changes in the Open-Hearth.—Mr. R. Addie[1] discussed the chemical changes occurring in the acid open-hearth in a paper read before the City Analysts' Society of Glasgow. He gives the following average analyses of bricks and blocks used as furnace linings in some Scotch steelworks :

	Silica.	Alumina.	Ferric Oxide.	Lime and Magnesia.
Eglinton silica blocks, -	96·72	1·5	1·36	traces
Glenboig silica blocks, -	96·16	1·96		1·88

Lime in the form of milk of lime is used as a binding agent for the silica of the bricks, but the amount must be small, otherwise it will flux the silica.

[1] *Engineering*, Vol. 52, p. 103.

In the acid process the bottom of the furnace is lined with white sand, mixed with a varying proportion of red sand, and then hardened by fritting with heat.

The composition and the changes that take place in the producer gas in its passage through the flues of the furnace are shown by the following analyses:

	I.	II.	III.
Carbon dioxide, - -	5·2	5·6	7·36
Oxygen, - - -	0·4	0·52	0·40
Carbonic oxide, - -	22·0	21·88	21·88
Hydrogen, - - -	7·2	7·04	7·56
Marsh gas, - - -	3·2	3·56	2·60
Nitrogen, - - -	62·0	61·4	60·2
	100·0	100·0	100·0

The samples were taken by means of a long tube. I. From the flue near the producer before entering the furnace; II. From the bottom of the regenerator; III. From the top of the regenerator.

From the entrance of the gas into the furnace the process is one of oxidation, for during the melting-down period the charge of pig and scrap is subjected to an oxidising influence, about half the silicon and one-third the manganese forming silicates; nearly one half the carbon forming carbon monoxide and dioxide, and a little of the iron is oxidised. This is elucidated by the following example of a 20-ton charge, consisting of 14 tons of pig iron and 6 tons of scrap. The whole has the following composition:

	Combined Carbon.	Graphite.	Silicon.	Sulphur.	Phosphorus.	Manganese.
I., -	0·3	3·7	2·08	0·02	0·05	0·72
II., -	1·76	—	1·35	0·02	0·05	0·40

No. I. is before melting. No. II. after melting.

Iron ore is then added to afford employment for the reducing agents present. Most of the manganese is oxidised at the stage termed "coming to the boil," and all of it before the boil actually takes place, and this with the silica forms silicates. No more carbon is oxidised until the boil has actually begun.

The metal in the 20-ton charge, to which 2 tons of ore has been added, has now the following composition:

Combined carbon,	1·655
Silicon,	0·196
Sulphur,	0·022
Phosphorus,	0·050
Iron,	98·077

When the surface of the molten metal is almost quiescent the bath has the following composition:

Combined carbon,	0·155
Silicon,	0·004
Sulphur,	0·024
Phosphorus,	0·050
Iron,	99·767

The sulphur has probably increased by absorbing sulphur from the gas. To complete the charge, 3 tons 16 cwts. of ore, together with 5 cwts. 3 qrs. of limestone are added, the latter being required to make a suitable slag. In order to neutralise the bad effects of sulphur and phosphorus, rich ferro-manganese is added. For a 20-ton charge about 3 cwts. 3 qrs. 12 lbs. are necessary, so as to ensure about 0·4 per cent. manganese in the finished steel. The analyses of the slag are as follows:

	Before and	After addition of Ferro-Manganese.
Silica,	55·60	55·60
Ferric oxide,	3·88	2·56
Ferrous oxide,	25·78	24·26
Manganous oxide,	4·25	6·41
Lime,	8·45	8·43

Manganese also tends to remove suspended particles of slag from the molten steel, as well as counteracting the bad effects of phosphorus. The analysis of the steel after-casting is as follows:

Carbon,	0·170
Silicon,	0·004
Sulphur,	0·023
Phosphorus,	0·048
Manganese,	0·346
Iron,	99·409

Open-Hearth Plant.[1]—Fig. 109 shows a plan of an open-hearth plant at the Homestead works of Carnegie, Phipps & Co. There are two 15 ton, five 20-ton, and one 35-ton furnaces of the Lash type. The furnaces stand in two opposite rows, and between them are two ladle roads running to the casting pits. The tapping holes are one foot above the floor level. In front of each furnace is a 60-ton hydraulic ladle crane, a ladle pit, and a 5-ton slag and skull crane. These cranes are top-supported and built of H-beams. After tapping, the ladle is lifted out of the pit, placed on a four-wheeled bogie carriage, and drawn by a locomotive to the casting pits. There are two casting pits standing back to back, each served by separate cranes. The Lash furnace is fired by natural gas, it is elliptical in shape, and is 20 feet long and 16 feet wide inside for a 25-ton furnace. The end flues of the air ports are 5 feet wide, and the gas is admitted late, near the junction of the flue with the hearth, in order to prevent the cutting action of the flame. It enters at a pressure of one ounce per square foot. The flues leading to the stack are filled with checker work, to form the regenerator.

In Fig. 109, *AA* are the furnaces; *BB* ladle pits; *CC* skull and slag cranes; *DD* ladle cranes; *EE* ingot cranes; *GG* casting pits; *H* ladle roads to casting pits.

[1] *Jour. of Iron and Steel Inst.*, American Vol., 1890.

Several attempts have been made to introduce a blast of air into the open-hearth. Ponsard modified the Pernot furnace by the addition of two twyers inserted in the side lining. These twyers operate alternately, with the object of hastening the first part of the process. In this case the rotating bed only moves half a revolution, since in a complete revolution the twyers would be alternately in and out of the metal. The central spindle, on which the hearth rotates, is made hollow, and through this the blast passes to

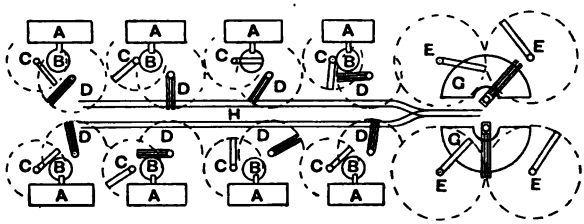


FIG. 109.

the twyers. It was the opinion of the celebrated observer Gruner, that as the after-blow is an essential part of the basic Bessemer process, unless a similar contrivance to that of Ponsard be adopted in the basic open-hearth, mild steel, free from phosphorus, could not be produced from common phosphoric iron. Recalling to mind these and similar attempts to add a forced blast to the open-hearth, Lencauchez introduced to the Iron and Steel Institute in 1894 an open-hearth furnace with a stationary hearth, and having a water-cooled twyer to force a blast of air through the roof in the form of jets. It is claimed that these jets cause an intimate mixture of the hot air and gas as they enter the hearth, and also increase the rapidity of the refining, in virtue of the quicker oxidation during the melting stage. The introduction of 10 to 15 per cent. of cold air into the furnace by means of the blast might be

supposed to lead to a cooling effect, but this is compensated for by the more thorough mixture of gas and air from the regenerators. The metal is fused at a relatively low temperature in an oxidising flame to effect desulphurisation by aid of the manganese in the pig iron employed. By slightly raising the temperature nearly all the silicon and phosphorus are oxidised, and the bath is then rabbled. Lime is added to take up the last trace of phosphorus. The object then of blowing is to increase the output, and refine as much pig iron as possible by means of the air. This means the production of less slag and its removal at a moderate temperature, for the waste in all steel melting furnaces is in a great measure commensurate with the time occupied in melting the charge.

Swedish Open-Hearth.—In Sweden, where wood fuel is largely used, a special type of gas producer is necessary in connection with the open-hearth furnace, and the latter of late years has been built with a high roof, domed arch, and with alternating or "gallery" ports for gas and air. By this means the pig iron is partly melted in the hot-air currents, coming from the ports, and the silicon and carbon are partly oxidised during the fusion. Fig. 110 shows a 10-ton furnace. It has been found when sulphurous fuels are used, that the metal is less liable to take up sulphur during the melting when gallery ports are used, instead of having gas ports below and air ports above. The ports incline downwards to the hearth. 80 cubic feet of regenerator space per ton of steel is allowed. The valves are American lift-and-drop dish valves, which rest against water-cooled seats. The air regenerators are the same size as the gas regenerators, as gas from wood and peat is colder than gas produced from coal.

Three kinds of steel are made in the above furnace: (1) mild steel containing 0·15 per cent. carbon; (2) tool steel

with upwards of 0·40 per cent. carbon; (3) steel castings.

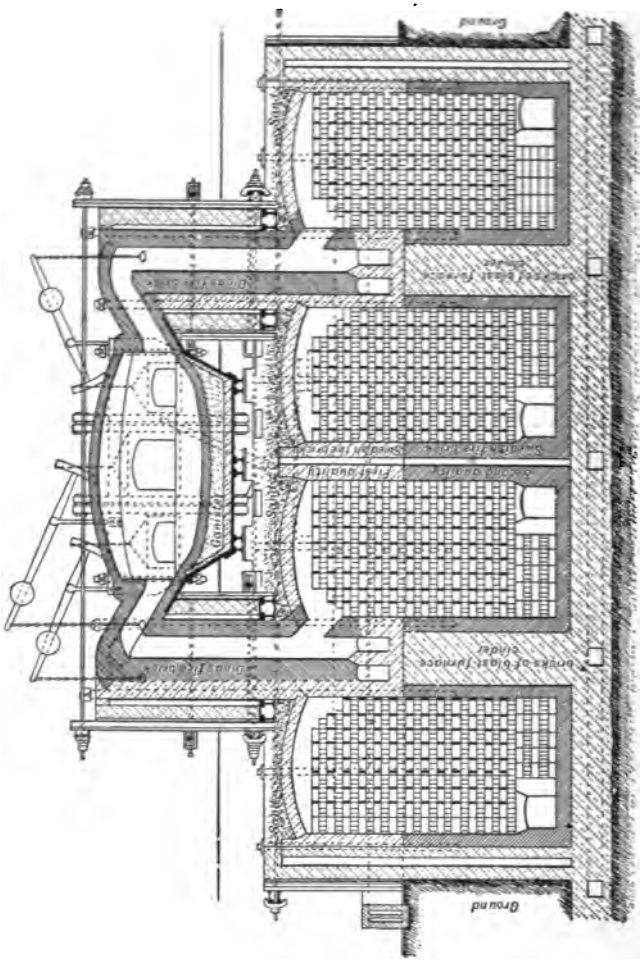


FIG. 110.

For No. 1 variety, pig iron practically free from sulphur is used, and the scrap iron is selected so as to be free

from rust, as rust may contain sulphur. The pig and scrap are charged at the same time, and when melted the requisite ore is added. The main object is to obtain soft metal as free as possible from sulphur and oxygen, so that little ferro-manganese is required to be added. For telegraph wire no manganese should be in the steel. Wood fuel is an advantage where the sulphur is required to be very minute. If the charge becomes too cool during the working, the metal will be red-short. 0·25 per cent. of manganese is said to decrease the toughness more than 0·04 per cent. of phosphorus, which is the highest amount admissible in first-class steel. If the charge gets too hot silicon will pass into the steel.

In the manufacture of tool steel in the acid-lined furnace, phosphorus must be practically absent, and fuel as free as possible from that element is therefore used, as well as good quality pig iron and scrap. The process is so conducted that a good steady heat is maintained, so as to get metal nearly free from gases during tapping, and hence ingots free from blowholes, without too much tendency to "pipe." The great danger in making hard steel is in getting it too hot, which produces surface blowholes.

In making steel castings it is essential that the moulds should be made of proper material. A mixture of red sandstone and best quartz is used, ground to the requisite degree of fineness. A special preparation for facing the moulds consists of the German *kieselguhr* mixed with glue. In order to save the expense of keeping so high a temperature after the melt, a minute quantity of aluminium is added before tapping. Aluminium cannot be used in steel where the highest quality is desired, as it causes crystallisation; but this is to some extent destroyed by annealing. Aluminium, even in small quantity, diminishes the toughness of best steel.[1]

[1] *Amer. Inst. Mining Engineers*, 1894.

The Duplex Process.—This is a combination of the Bessemer and open-hearth, in which the pig iron is desiliconised in an acid-lined Bessemer converter and immediately afterwards introduced into the basic open-hearth to be dephosphorised and decarburised. The aim is to retain the merits of the Bessemer process, with its non-fuel consumption and rapidity, and to avoid its defects as regards its great loss of iron and the production of inferior steel to that of the open-hearth process. The actual loss is even higher than the normal acid Bessemer practice, so that the duplex system is not economical as a rule. Many successive duplex heats are destructive of the bottom, especially during the reaction on admixture. The time gained is probably more than set off by the oxidation. The steel works at Kladno, besides their basic Bessemer plant, have an open-hearth plant, consisting of one 12-ton furnace and one of 24 tons capacity, for the purpose of working up the crop ends and other scrap. The smaller open-hearth furnace is erected on the same level as the remelting furnaces, and about 15 feet above the larger one, so that it may be used also as a melter for the basic Bessemer converter. Experience has shown that, when working with a more siliceous and phosphoric pig iron, the heats require considerably more time towards the finish, owing to the necessity of adding much lime. The position of the two furnaces at different levels suggested the idea of dividing the work between them, so that the upper one might eliminate the main bulk of the silicon and phosphorus, and the lower furnace complete the refining. The plan of working was to charge nearly all the phosphoric and siliceous pig iron into the upper furnace and nearly all the scrap in the finishing furnace, adding to each the necessary quantities of lime, ore, etc. This method of working resulted in an increased output and a

reduction in the amount of lime and basic materials for lining, since the corrosive action of the slags was reduced. Another advantage is that the process may be worked with a much less proportion of scrap and higher proportion of pig iron.

Mr. Hibbert says: "In the basic Open-Hearth the most troublesome and destructive agent met with in the furnace is silica. It causes trouble by cutting and destroying the bottom, and by preventing, or at least retarding, the removal of phosphorus from the metal when present in considerable quantities. It is introduced in the form of sand sticking to the pigs from the sand bed in which they were cast, and is also formed in the furnace by the oxidation of the combined silicon in the iron. Experience shows, however, that the evil effects of the latter, especially in cutting the bottom, are not nearly as marked as in the case of the sand on the pigs. Most of the combined silicon is oxidised to silica after the charge is melted, when the bottom is not exposed to the action of the slag, except along the slag-line at the surface of the bath. In the slag itself, where the silica is all collected, it is diluted by the excess of basic material, and its corrosive effect practically neutralised. The sand on the pigs, on the other hand, begins the destruction of the bottom as soon as brought in contact with it at a sufficiently high temperature, which is early in the history of the heat. The motto of the basic open-hearth steel melter should be 'Beware of silica.' With great relief he would miss the 1 to 3 per cent. of sand commonly found on commercial pig, were it only absent."

"If those working this process claim that they can operate successfully with common sand pig, then it may be said that by using clean pig the limit of combined silicon permissible in the iron is raised so as to include nearly all grey

iron made, as far as that is concerned, and the special manufacture of basic pig will be reduced to the one condition of casting common grey foundry or mill iron in clean iron moulds. This will do away with the trouble from high sulphur in the low silicon pig now especially made for basic open-hearth work, and will also render useless the $1\frac{1}{2}$ per cent. of manganese, sometimes reduced in the blast-furnace and passing into the basic pig, with the especial object of the removal of sulphur. This manganese is practically all wasted in working the process."

"To avoid the sand and silicon difficulty by blowing the metal in an acid-lined Bessemer converter, after melting it in a cupola, may be effective, but it is expensive. The increased output can be more than met by putting the cost of the Bessemer plant into additional melting furnaces. The operations of the plant would then be simpler, and the different parts more independent of each other. In the acid open-hearth process, a little sand is sometimes a good thing to introduce to satisfy chemically the basic oxide of iron formed in melting scrap."[1]

On the Continent what is termed refined basic steel is made. The process is differentiated from ordinary basic practice both in the converter and open-hearth by the fact that the raw materials used are very low in phosphorus. Even acid steel may be passed through the basic furnace to refine it further. With highly phosphoric material there is a great tendency for the phosphorus to return into the metal from the slag, owing to its reduction by the carbon of the ferro-manganese. In the process under consideration, a basic furnace is charged with at most 25 per cent. of pure pig iron, 75 per cent. scrap, very little lime, and no ore. There is only a thin layer of slag, so that the flame has thorough access to the metal, and the pig

[1] *Jour. Iron and Steel Inst.*, No. 2, 1896.

iron is only used to afford carbon, and to protect the bottom from the scrap. The charge is rapidly finished; in fact, almost as soon as it is melted down. Both mild and hard steel may be made in this way. The pig iron used contains a little silicon and a little phosphorus.

Iron and steel scrap may be employed as long as it does not contain much sulphur, though it may contain phosphorus. In fact it may be cold-short, but not red-short. The amount of metal made containing both sulphur and phosphorus is very small, so that scrap of that nature is not to be feared. Scrap from basic steel works is extensively used, and also scrap from the puddling furnace; and it is even proposed to manufacture the scrap regularly, as attention need only be directed to the removal of silicon, sulphur, and cinder. In America the rotatory-furnace is used, and at Witkowitz small acid-lined converters are employed, and the molten metal run direct into the open-hearths, which give six or seven heats in twenty-four hours. Impurities are removed by oxidation, and recarburising is done with ferro-manganese or with free carbon. Poling is sometimes resorted to to accelerate mixing. To get rid of dissolved oxide, the metal is sometimes tapped into an acid-lined ladle, to which the ferro-manganese is added, and allowed to stand some time before casting. Ingots are generally cast from below in groups, and are often rolled without cogging or hammering, in which case some manipulation in the rolls is required to obtain fairly square plates. Generally only the mildest qualities of steel are made by this process.[1]

Bertrand-Thiel Process.[2]—This is a duplex open-hearth process devised with the object of more rapid and more

[1] *Trans. of Engineers and Shipbuilders in Scotland*, Vol. 51, pp. 227-248.

[2] *Jour. Iron and Steel Inst.*, No. 1, 1897.

economical working, both as regards time and materials. A great increase in the size of open-hearth furnaces has taken place of late years, and the output per furnace has been quadrupled by the Bertrand-Thiel process, even under unfavourable conditions. Two open-hearth furnaces are worked in conjunction, a small upper one in which common pig iron is melted and partly refined, and a larger one placed at a lower level in which the partly refined iron, together with all the scrap available and some ore are melted, and the iron completely refined. When working with a large proportion of scrap the furnace hearths need not be kept so deep, *i.e.* they may have less cubic capacity for a given weight of charge than when working with pig iron alone; as in the latter case greater additions of lime and ore are necessary. Moreover, when pig iron alone is used the charge boils up excessively, and may cause the slag to flow out of the furnace doors, so that some scrap is advisable to quiet down the metal. Silicon and manganese are practically eliminated in the first furnace, together with some carbon and phosphorus. About two-thirds of the carbon and one-third of the phosphorus are left to be removed in the finishing furnace. It will be seen from the above remarks, that if it be attempted to urge the rapidity of decarburisation in an ordinary single open-hearth furnace, the slag will rise so rapidly as to run out of the doors of the furnace. The greater rapidity of working in the duplex method is due to the fact of the impurities being slagged off in two stages; hence there is less slag present and more room for metal. In the lower hearth the metal which has been largely freed from sand and slag-forming elements, only causes a limited amount of slag to be produced.

In an ordinary open-hearth furnace the oxidation of the charge is chiefly confined to the upper part, where it is in

contact with the overlying slag and the lumps of ore, but in the Bertrand-Thiel process the hot metal from the upper furnace is run on to white hot scrap, which has become strongly oxidised, so that the oxidising influence is both at the top and bottom, and the metal is therefore more quickly purified. Moreover, at the high temperature of the Siemens furnace, there is a violent reaction between the metalloids and the oxide of iron and great internal heat is produced by their oxidation, which greatly assists in maintaining the temperature of the furnace.

A basic lining appears to be necessary, and this lining in the preliminary furnace to a large extent contributes to the success of the process. It might appear that by continuing the operation in the first furnace the metalloids would be so reduced as to avoid the use of a second furnace, but the difficulty is not so much in removing the bulk of the phosphorus as in removing the last portions, and it is in this respect that the second furnace is so necessary; at anyrate, to remove this portion of the phosphorus the silica in the slag must be kept low, and that means the use of purer pig iron. But one object of the process under consideration is the use, from common ores, of pig iron, high in phosphorus and silicon, and any process by which high quality steel can be produced from such pig iron is greatly to be encouraged.

Mr. Wailes states that "for working a charge under the same slag in a single furnace it was clear that after the bulk of the metalloids had been taken up and the oxide reduced to the required extent, they had to bring the whole of the slag to the necessary condition to take up the last traces. Tapping the slag was not an easy matter, and never complete and satisfactory; but supposing they could manage this fairly, they had to add fresh lime and oxide, and lose heat. The metal might be hot and molten, but

they wanted a fresh furnace more than a fresh slag, and that was the pivot on which the whole thing turned. After the furnace had been driven at the highest possible heat for the roughing down, it was in the least suitable condition for the exact and more refined operation of finishing. A furnace in the best condition, with the proper cinder, must be of vital importance in the difficult refining stage, and instead of complicating must greatly simplify things. Any accidental mixing of any acid part of the structure of the furnace is a serious hindrance, especially near the end of the working of a basic charge. Doubtless the plan of transferring the metal to a finishing furnace may have the most marked effect on the open-hearth basic process."

Mr. Bertrand sums up the advantages of his process as follows:

1. The possibility of working with any proportion of pig iron alone, and of then using an ordinary cheap phosphoric and siliceous pig, producing therefrom a steel of excellent quality. 2. Materially increasing the yield of metal by reduction from the ore added. 3. Increasing the actual work done per furnace; *i.e.* two primary and one finishing furnace, working together upon the combined plan, and using phosphoric pig, will produce more steel in a given time than three furnaces working separately.

The process as now worked may be used for pig iron and scrap, for cold pig iron alone, or for molten metal from the blast furnace. For pig iron alone the finishing furnace is one-third larger than either of the primary furnaces. From 80 to 90 per cent. of the charge may be put into the primary furnaces and the balance into the finishing furnace. For pig iron and scrap the finishing furnace should be twice as large as either of the primary furnaces. About three-fifths of the charge is put into the primary furnaces

and the remainder in the finishing furnace. For molten metal direct from the blast furnace only one primary and one finishing furnace are required, and the latter need only be one-third the larger of the two About 80 to 90 per cent. of the charge is put into the primary and the remainder (pig iron and scrap) is charged cold into the finishing furnace.

Talbot Process.[1]—This is a continuous basic open-hearth process, devised by Mr. Benjamin Talbot. Instead of treating each charge as a separate heat, and tapping it when finished into the ladle, only a portion is run off at intervals, and a fresh supply of molten pig iron is added to the residue left in the furnace. In ordinary open hearth furnaces, while many attempts have been made to run molten pig iron direct on to the bed, such practice has generally led to a rapid destruction of the lining. In the Talbot process a large quantity of molten metal is left in the furnace, sufficient to cover the bed and thus to protect the lining from the corrosive action of the slags. The aim is, to approach the rapidity of working of the Bessemer process, and at the same time to obtain the high yield of the open-hearth. The following conditions are therefore essential: 1. The use of fluid metal from the blast furnace, mixer, or cupola, to avoid loss of time and oxidation by air during the melting in the open-hearth and to utilise the heat of the molten metal. 2. The oxidation of the metalloids should be effected entirely by means of solid oxides of iron, and not by the action of the air. 3. Maintaining by suitable means a large reserve of heat to keep the oxidising slags and metal in a fluid condition. To prevent the slag from corroding the lining it must be run off from the surface of the metal, and to do this effectually a tilting furnace seems necessary.

[1] *Jour. Iron and Steel Institute*, No. 1, 1900.

The furnace used by Mr. Talbot is a basic-lined tilting furnace of the Wellman type, capable of holding 75 tons. The pig iron used at Pencoyd, Pennsylvania, has a composition: Carbon 3·76, silicon 1·0, sulphur 0·06, phosphorus 0·90, and manganese 0·40 per cent. This is melted in a cupola. Suppose the furnace to be charged on Sunday night with 50 per cent. molten cupola metal and 50 per cent. scrap; this is worked for steel in the usual way. When the charge is finished, about one-third, 20 tons, is poured off into the ladle and cast into ingots. No slag is run off with this portion of steel. Oxide of iron in a finely divided state is then thrown on to the slag, and as soon as it is melted, about 20 tons of molten cupola metal are run in to replace the steel tapped off. An immediate very active reaction takes place, during the continuance of which the gas is cut off from the furnace. Carbonic oxide is copiously evolved, and after this boil has been on for fifteen minutes, the slag is poured off and the bath of metal worked into finished steel by the help of fresh additions of iron ore and lime. Another 20 tons are again tapped off and a similar quantity of molten metal added as before. These operations are continued for a week and the furnace completely emptied on Saturday.

This method of working with a tilting furnace avoids the difficulties arising in intermittent practice during the melting-down stage; such as: 1. The low temperature which prevails during the melting down favours the oxidation of silicon and iron, with the formation of a relatively siliceous and ferruginous slag, which attacks the furnace lining before it is covered with a protective layer of molten metal; 2. the difficulty sometimes of getting a sufficiently high temperature to again deoxidise the initially oxidised iron; 3. the moderate temperature shortly after melting down prevents the decarburisation

from being rapid. Now in the continuous process there is only one melting down each week, and the above troubles only arise once a week, instead of at each charge, as the furnace is partly full of molten metal and thus protects the bottom. The added iron, whether molten metal or scrap, is at once plunged into the molten bath, and therefore is not exposed to a prolonged oxidation by the air, and the silica finds a large mass of basic slag which dissolves it. On this account the amount of silicon in the pig iron employed may be much higher than is usual with metal used in the ordinary furnace, hence commoner brands of iron may be used. Also each fresh addition of iron is added to the furnace at the requisite temperature for immediate and rapid decarburisation.

The fuel consumption is about 5 cwts. of coal per ton of steel produced. Mr. Talbot considers that this will be considerably reduced in the future. The amount of deoxidisers required for this process is 25 to 33 per cent. less than for ordinary furnaces, so as to give the same amount of manganese in the finished steel. The conditions formulated by Mr. Talbot are then fulfilled—liquid metal is used without destroying the hearth; oxidation is effected by oxide of iron, with concentration of the heat, due to the chemical action in the bath and the combustion of the carbonic oxide.

With reference to addition of solid scrap, experiments were tried to ascertain whether saving of time could be effected by thus diluting the carbon and phosphorus, but the chilling effect was so pronounced that the heats could not be made as rapidly as when the impurities were eliminated by the usual oxide of iron additions. In fact if it were possible to add the basic additions in a liquid condition the temperature of the bath would be benefited. In some cases, as in highly siliceous pig iron, it may be

expedient to have a mixer between the blast furnace and the open-hearth furnace, or to have a preliminary refining furnace as in the Bertrand-Thiel process.

Rotatory Furnaces.—Tilting furnaces of both the Campbell and Wellman type have been in somewhat extensive use for some years. They are of cylindrical shape and rotate about their long horizontal axes, and may be tilted forward for tapping either by being rolled along a flat path, or by being rotated about their own axes on live rings of rollers. In the Campbell furnace the motion is effected by a horizontal hydraulic cylinder. The air and gas ports are fixed, the furnace having an oval hole at each end for the entrance and exit of the gases. Each hole is only partly closed by the rotation of the furnace. There is a slight clearance between the ports and the furnace, both being faced with water-cooled iron plates. The portion of the ports nearest the furnace is separate from the rest and is removed for repairs after about 50 heats. At one works the charge is 80 per cent. molten pig from the blast furnace and 20 per cent. scrap. The tilting furnace requires relining after about 200 heats. One advantage of such a furnace is, that the tap hole is normally above the metal. The air is excluded by a little loose material, which is removed before tilting. This is a great advance on the ordinary furnace where the metal is above the tap hole, and the latter can only be trimmed when the furnace is empty. Open-ended boxes are raised by a crane to the open door of the furnace, which is tilted about 30 degrees, and the contents poured in.

The Potter tilting furnace, of 15 tons capacity, rocks about a transverse instead of a longitudinal axis. Four doors in the top admit of charging by an overhead crane. Oil is used as fuel instead of gas, being blown in by steam jets at either end, the air only being previously heated.

A hydraulic cylinder at the back end rocks the furnace, which rests on knife edges at the centre of its length. When tapping, a kind of forehearth is fixed to the front end of the furnace and the back end is raised, so that the metal flows into the forehearth, and from this, through a hole in the bottom into the ladle.

The Wellman furnace, Figs. 111 and 112, is a long horizontal chamber, resting on a pair of racks, and rolling on them by means of the segments of an enormous pinion. The rolling motion is given to it by large, nearly vertical hydraulic cylinders, and when tapping the furnace is tilted forwards, so as to depress the tapping spout, through which the metal is poured. The rolling surfaces are provided with rack-work, which keeps the furnace parallel without supporting any of its weight. In order to tilt the furnace water is admitted to the top end of the cylinder. The gas and air ports are of novel construction. The two passages leading from the regenerators and the ports terminate in two water troughs on the level of the charging floor. The brickwork of the ports is enclosed in a metal cage, but, instead of being fixed, it moves on flanged wheels running on rails, which enables it to be moved a few inches to or from the furnace end. When melting is in progress the ports are moved up to the surface, so that the face plates are in contact. When ready to pour the ports are moved away. A special kind of ladle is also used, attached to the front of the tapping hole, and forming a part of the structure. This ladle has two pouring holes and stoppers. When the furnace is tilted for pouring the metal and slag flow into the ladle and stand at the same level as the metal in the furnace. Trains of casting bogies, each containing two moulds, are then brought under the teeming holes of the ladle, and two moulds can be filled simultaneously.

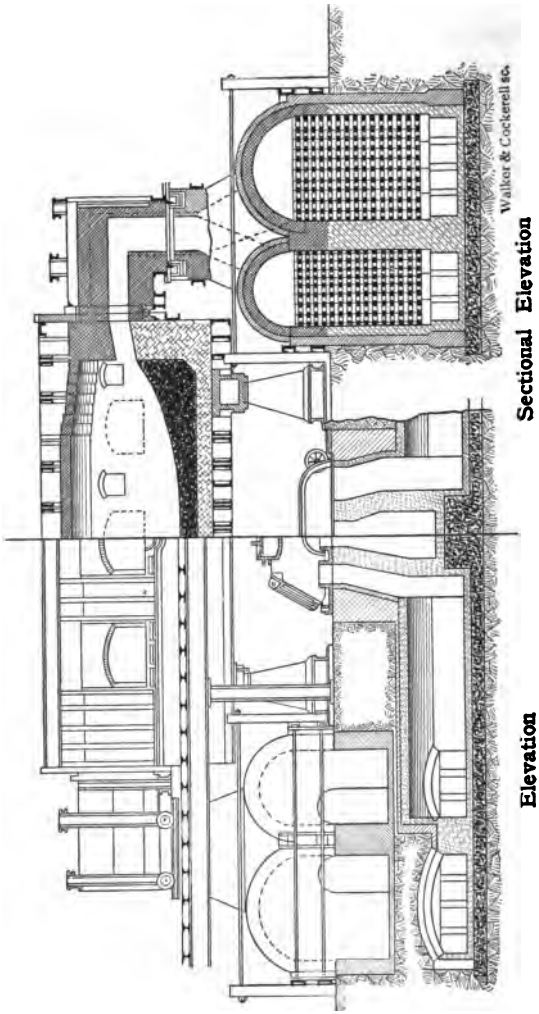
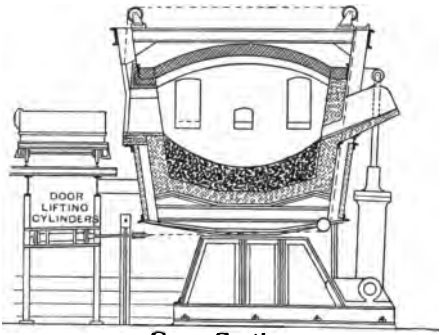


FIG. 111.

The regenerative chambers are arranged in pairs at each end of the furnace, and extending under the charging platform. The body of the furnace was originally round or oval in section, and enclosed in steel plates somewhat like a boiler, but now is more rectangular, which gives greater strength. The whole furnace is enclosed in a strong cage, constructed of plates, channel, and angle bars, while stout tie-rods bind the two ends together. The furnace top, sides,



Cross Section.

Silica Magnesite

FIG. 112.

and outer layer of the bottom are lined with silica and magnesite bricks. The inside or basic portion of the bottom is made with magnesite, which is burnt on in thin layers about one inch thick, at a steel-melting heat. The air-reversing valves are of the usual butterfly pattern. The gas-reversing valves consist of two mushroom valves, machined on their bevelled edges. Both valves and seats are water cooled. There are three charging doors, operated by pneumatic cylinders through wire ropes, the leads being so arranged that the doors are kept closed while the furnace is tilted. The angle for tilt is 25 degrees for pouring, and is regulated by stops which come in contact with the upper covers

of the hydraulic cylinders when the extreme angle has been reached. By a simple mechanism the stops can be thrown out of gear, when further tilting is required to drain off the slag.

Eyerman Furnace.[1]—This type of open-hearth furnace was patented in 1898. The system proposed was based on the general opinion that open-hearth steel is superior to Bessemer metal for many purposes, the inferiority of the latter being due to the blow being too rapid to permit of keeping pace with the chemical reactions of the metal in the converter, by means of exact chemical analysis; hence the judgment of the quality depends on the physical senses of the assayer. But since the introduction of the "mixer" as an intermediary between the blast furnace and the converter, the composition of the metal before addition to the Bessemer vessel can be accurately determined and any desired quality of steel produced. Eyerman, therefore, in his process combines the Bessemer process with that of the Open-Hearth. The furnace is of the tilting type, actuated by means of hydraulic cylinders or worm gearing; it can be turned or tipped on rollers, or segmental rockers that roll forward on a flat surface. The furnace itself is built inside a structure of girders and plates. The interior is built in four segmental divisions, formed of arched brickwork, two of which serve as hearths for the production of steel, and of the latter, one is narrow, and provided with air nozzles similar to those of a Bessemer converter. Along the exterior wall of the furnace a wind box is built for receiving the air.

In order to blow pig iron, preparatory for the open-hearth process, the furnace is turned round until the blowing hearth occupies the lowest position, and the iron is poured in through the charging spout. The gases evolved

[1] *Jour. Iron and Steel Inst.*, No. 1, 1902.

during the blow pass into the regenerative chambers. On completion of the blow the furnace is turned down, and the metal flows into the melting hearth and the blast is shut off. The Open-Hearth process is then ready to begin. Addition of ore and scrap are made through side doors, and the charge worked off in the usual way. The slag may be poured off through the spout during the process, and the finished metal is also tapped off through the same spout.

Eyerman next conceived the idea of utilising the waste gases of the blast furnace for heating the open-hearth. The gases from the blast furnace are first passed through coke towers, placed on each side of the furnace, for purifying and improving the gases. The gas is then passed through a reversing valve into the regenerative chamber, where air for combustion is admitted in the usual manner. The gas enters at the bottom, is heated by the hot brickwork, and rising to the top passes out through a flue which leads to a coke tower, and from this to the melting hearth of the furnace.

The novel features claimed for this furnace are: 1. The employment of waste gases. 2. The insertion in the gas uptake of a chamber containing carbon for improving the gas, by which carbon dioxide is changed to the monoxide. 3. The application of air nozzles to one of the hearths. By imparting a rocking movement to the furnace with an electric motor, these can be brought nearer or farther from the metal bath. 4. The carrying out of every known furnace process in a vessel heated by blast furnace gas. 5. The combination of the fining process with the usual finishing process in one and the same vessel.

The objections to the use of blast furnace gases in the open-hearth are, that the latter is then dependent on the regular working of the blast furnace, and if the gas were shut off during the working of an open-hearth charge the operation

would be stopped. Hence an independent gas producer is requisite to forestall such a case. Moreover, molten iron poured direct on to the bed of an open-hearth exerts a strong cutting action, but this largely depends on the quality of the refractory material employed.

Large open-hearth furnaces began to attract the greatest attention about the year 1885, especially in America, the land of colossal undertakings. So large indeed have the furnaces become that nothing under 50-ton furnaces are considered worth attention. One of the most striking statements is, that these large furnaces do not turn out more metal than the smaller ones, say 15 to 20 tons per cast. This is due to the fact that the large furnaces make a less number of casts per 24 hours. The Carnegie Company have twelve 50-ton furnaces, placed in two rows, and using natural gas as fuel. The new steelworks of the St. Clair Company, Pittsburg, contain twelve 50-ton stationary furnaces, and a 300-ton mixer, supplied from 450-ton blast furnaces. The furnaces are raised 10 feet, so that the casting floor is on the ground level. The Cambria Steel Company, Pennsylvania, have seven 50-ton furnaces, of which one is acid and the others basic-lined. The Pencoyd Steelworks use a 75-ton furnace, working 60-ton charges. At Frodingham a furnace of 100-tons capacity is in operation.

Charging Machines.—Charging arrangements have been brought into great prominence of late years, especially in America, where labour-saving appliances are in great demand, in order to reduce the time required to charge a furnace, and to avoid the use of so much costly hand labour. Early machines were worked by hydraulic power, the movements being therefore necessarily slow, and there is loss of power when they move with less than maximum resistance. Moreover, the constant supply of high-pressure

water to a machine travelling longitudinally over a considerable distance is attended with difficulty, and india-rubber pressure pipes, if used too near hot furnaces, are costly and difficult to maintain. The machine is deficient in strength and rigidity, and only suitable for light loads. The use of electricity as the motive power has solved the difficulty. One of the newest types, made by Mr. Wellman,[1] is given in Fig. 113. It shows a cross section of the furnace, the charging bogie with a charging box upon it, and the charging machine itself. The main carriage is rendered stable by extending it 3 feet longitudinally. At the four corners, box columns are erected which are surrounded by a framework consisting of a pair of channel section beams, carrying rails on which the charger truck runs. Downwards from the charger truck projects a strong bracket, ending in double-eyed bearings, which carry a trunnion sleeve. Into this sleeve is threaded and secured with a back collar the charging bar. On the after end of the latter is carried the operator's platform, the tail end of which is connected by two rods with the pins of two cranks, keyed symmetrically to a shaft running across the charger truck frame at its rear end. A motor carried on the truck is connected by gear with this shaft. By switching on the current the operator can rotate the crank shaft in either direction, and so move the charging bar up or down. On the charger truck is also mounted a motor and gear for moving it, and the charging bar and all connected therewith, towards or from the furnace, by operating on the front axle and wheels.

The charging bar is hollow, and the interior is occupied by a steel rod connected with a lever on the operator's platform. By this means when the bar has been lowered into the socket of the box, the operator can lock them together or unlock them at will.

[1] *Jour. Iron and Steel Inst.*, No. 1, 1897.

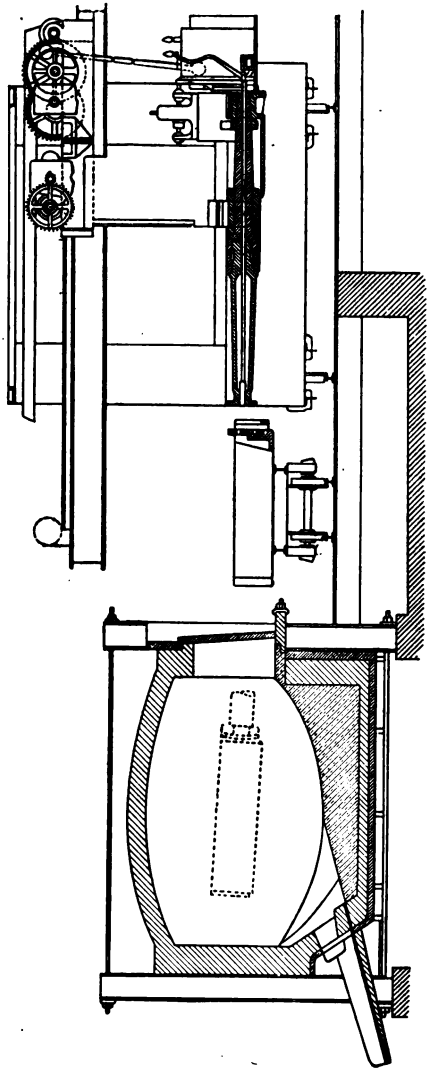


FIG. 118.

The motor and gear for moving the machine longitudinally is upon the main carriage. The motor and gear for twisting the charging bar is upon the operator's platform. The motor for producing the requisite movements is 25 horse-power, and that for twisting the charging bar $3\frac{1}{2}$ horse-power.

The charging boxes are 6 feet long, 2 feet broad, and $1\frac{3}{4}$ feet deep, giving a capacity of 21 cubic feet. This will hold a ton of material, and the machine will pick up and empty one a minute. One machine will serve for six 40-ton furnaces, but two machines are recommended in case of a breakdown.

Metal Mixer.—This is a vessel for receiving the liquid-iron from blast furnaces, so as to obtain a more uniform metal for use in the Bessemer or open-hearth process, than is the case when the metal from each tapping is cast into pigs, as the accidental irregularities in the furnace products are thus neutralised, and the working of a steel-works and that of a blast furnace-plant are rendered more independent of each other. The mixing is no longer effected in the ladle; a more uniform composition of the iron and an even temperature become possible, with the result that the regularity in composition of the steel made becomes more certain.

The addition of lime, required for the basic Bessemer plant, may be more accurately determined, and a saving of 2 to 3 per cent. effected; the value of the basic slag made is improved; the losses of blown-out metal are diminished; the duration of the blow is shorter and more certain with different charges, the metal taken being weighed as it leaves the mixer; this again enables a saving to be effected in the spiegel-eisen and ferro-manganese used; and the metal blown being of fairly constant composition the converter linings and bottoms are less attacked. Possibly the mixer might be

used with advantage in large foundries, which make large castings from molten metal, tapped direct from the blast furnace.

The mixer is valuable as a reservoir of heat, since the large mass of molten iron always present retains sufficient heat to keep it liquid for long periods, only a portion of

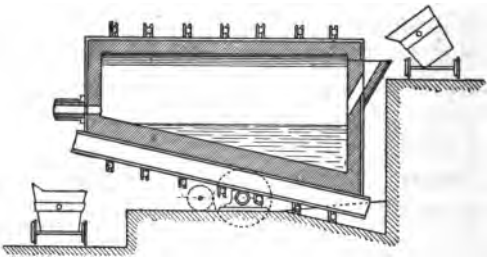


FIG. 114.

the contents being poured into the ladle as required for the steel furnace.

Figure 114 represents a metal mixer. It consists of a wrought-iron box, heavily braced together, and lined with a 9-inch course of fire-brick. It is mounted on strong trunnions, and rocked by two pairs of 12-inch by 30 inch engines. At the Duquesne works the mixer is of semi-cylindrical form, with hemispherical ends, and an arched roof. It rests on rocker bands, which run on roller bearings and is tilted, for pouring the metal into the ladle, by a ram at one end. The shell is of steel plate, lined with 18 inches of refractory material, and the inside dimensions are 18 feet by 12 feet, and it holds 200 tons of iron. An electric over-head crane picks up the ladles and carries them over the hopper of the mixer. In some works the tilting open-hearth furnace is used simply as a mixer.

CHAPTER XXIII.

CASTING OF STEEL.

THE operation of pouring molten steel requires great care so as to get compact and weldable ingots. The higher the temperature of the liquid metal the more gas it absorbs, and as the temperature falls the absorbed gases are liberated; if, however, the steel be poured at too high a temperature some of these gases will remain after the surface has solidified, and produce a honeycombed appearance; the cavities are termed blow-holes.

A ladle of Bessemer- or Siemens-steel is a seething mass, and if poured into the moulds in this state is very liable to produce unsound castings. About forty years ago Bessemer used a siliceous pig iron for mixing with the spiegel eisen, in order to quiet the steel, and ensure greater soundness, and if the blow was not too hot, it was fairly successful. Great caution, however, should be exercised in adding substances to neutralise the effects of impurities, as more injurious ingredients may be introduced, making the steel brittle and too hard. A great advantage is gained by mechanical agitation of the metal, and for this purpose Mr. Allen lowers into the ladle of steel a rotating paddle, the motion of which facilitates the escape of the gases, and in a great measure prevents blow-holes in the ingots. By

the aid of this agitator, and the use of ferro-manganese alone as a quieting agent, good sound castings are obtained.

"Glazed" iron (which is iron with silicon) and a triple compound of iron, manganese, and silicon, termed "silicon-ferro-manganese," are now largely used for adding to molten steel to produce sound ingots. With regard to this subject, Mr. Pourcel says: "On analysing a sample free from blow holes, silicon is always found; whilst a honey-combed sample contains interposed slag, but no free silicon."

Silicon is more oxidisable than carbon, so that solid silica SiO_2 may be formed instead of gaseous carbonic oxide CO. Moreover, silica forms with oxide of iron and oxide of manganese a fluid slag, which largely liquates out when the steel is solidifying. This is especially important in basic steel, where the ordinary slag is less fusible, since it is the slag between the particles which makes the steel red-short. The two reducing bodies, manganese and silicon, act simultaneously in reducing the oxide of iron formed while the liquid metal is exposed to the air.

Müller considers that silicon acts by increasing the solvent action of steel for gases, and thus retaining the gases in solution instead of allowing them to be liberated. He also suggests that the beneficial effect of adding spiegeleisen, is partly due to the evolution of carbonic oxide which ensues, sweeping out some hydrogen at the same time, thus reducing the liability to blow-holes. The different opinions as to the cause of blow-holes may be summarised as follows:—1. By gases in solution. 2. By gases formed by the action of the air on the metal during pouring. 3. By air and gases carried into the metal mechanically when the metal is being run into the moulds, the viscous mass preventing them from escaping.[1]

[1] See *Steel*, by Howe, § 210, p. 134.

In large complicated castings due allowance must be made for contraction, for steel contracts twice as much as cast iron; therefore large castings are often made in two or more pieces to avoid internal strains. In consequence of the contraction, steel castings have often been destroyed when left in the moulds to cool. They should be removed as soon as possible and placed in the annealing furnace while hot, since the reheating of cold castings is injurious, especially in large work. Tempering in oil is occasionally resorted to, which raises the tensile strength, and increases the elongation, but diminishes the ductility.

Segregation.—Iron and steel are often far from homogeneous in their structure, as some of the constituents remain liquid after the rest has solidified. This is notably the case with large castings, such as steel ingots. Howe defines segregation as a concentration inwards, and liquation as a movement of matter towards the exterior. In a liquid complex mass there is a tendency for a constituent to crystallise out in the pure state, and the residue left may be the segregated portion. It is usual to speak of the segregated substances as "metalloids," although some may be metals and even compounds, such as slag. Segregation is not due to imperfect mixing, leaving a portion undissolved, but to a separation of certain constituents from a mass, uniform while in the liquid condition, but non-uniform after solidification. Segregation is often harmless, and even beneficial, by concentrating the impurities in the axis of the ingot or towards the top.

The causes of the separation of certain constituents of steel is attributed by Howe to the struggle between crystalline force and surface tension, aided by gravity; on the one hand tending towards differentiation and on the other towards diffusion. As the temperature sinks towards the freezing point, the surface tension increases, the different

constituents tend less powerfully to diffuse among each other, and more to draw apart in drops. Further, as the complex molten mass cools past the freezing point of a certain potentially present compound, this compound tends to form, to solidify, to crystallise, to expel the more fusible residue, in the same way as a salt in crystallising expels the mother liquor, which is gradually driven towards the last freezing region. As time is required to effect any considerable separation, we may infer that slow cooling favours segregation.[1]

The portions which segregate are probably compounds that fuse at lower temperatures than that of the main mass, or compounds that differ greatly in density from the main mass. The strong affinity of carbon, phosphorus, and sulphur for iron, as compared with that of manganese, and the greater fusibility and lower densities of carbides, phosphides, and sulphides than that of manganese-iron alloys should favour segregation of carbon, phosphorus, and sulphur. In steel, phosphorus segregates the most, and next to it comes sulphur. In fact, these elements often segregate together. Carbon is very liable to segregation, generally in conjunction with other elements. Silicon and manganese are less liable to segregation than either of the above-mentioned elements.

Moulds.—Turner's system of casting steel ingots is specially contrived for the ingots to be run from the bottom, having runner bricks set in the bed after the manner of the old "hen and chickens" pattern moulds. Its chief features are the grouping of several moulds in one ingot mould casting, the combination therewith of the piling of the moulds one on the top of the other in the casting pit, and the insertion of a small clay division brick in a hole in the top of each mould. In this way the steel

[1] *Metall. of Steel*, p. 204.

rises from the lower row of moulds into the second row, and from thence to the third row, etc., so that 120 ingots can be cast, containing 10 to 15 tons of steel cast through one runner pipe.

The moulds in which Bessemer and open-hearth steel are cast are made of cast iron or steel, open at both ends and rectangular or octagonal in section. They are made to

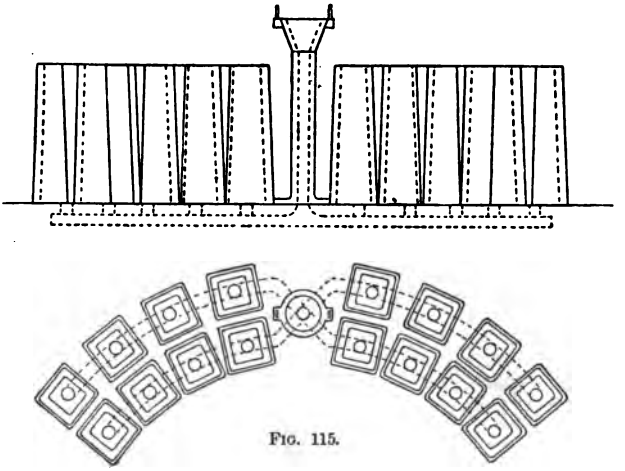


FIG. 115.

taper considerably, being larger at the bottom than the top, so as to allow of readily stripping from the ingot shortly after casting. The usual method has been to fill each mould separately, or to cast in groups as mentioned above. For rails the ingots are about 14½ inches square and weigh 25 to 30 cwts. each. Large ingots for other purposes may be 19½ inches square and weigh 50 cwts. each. The moulds are generally arranged in a shallow pit in a semicircle, so that the ladle crane may bring the nozzle of the ladle over each one in succession. Sometimes when an ingot is cast, it is stoppered down by throwing some sand on to it and

then covering with an iron plate, which is fastened down by a cross-bar and wedges. In group moulds, Fig. 115, they are generally arranged round a central one, somewhat taller than the rest, into which the metal is run, and passes from the bottom to the bottoms of the others by means of fireclay tubes or passages. Hence the metal

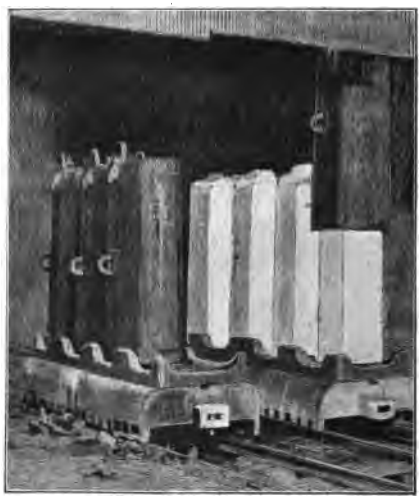


FIG. 116.

rises in the moulds from the bottom to the top. A plan now largely adopted, especially in American works, is to have the ladle stationary, and a bogie truck carrying two moulds is run under the nozzle of the ladle for teeming. The bogie then conveys them away, and another pair is brought under the tap hole, and so on in succession. Bogies with moulds and stripping arrangement are shown in Fig. 116.

Piping.—The defects of piping and blow-holes in ingots are due to widely different causes. The former is produced

by shrinking of the material during solidification. As soon as the ingot has been cast, that part of the molten mass which is in contact with the walls of the mould solidifies very rapidly, forming at the same time an outer crust or shell, the shape and size of which is not subject to any subsequent appreciable change, thus determining the outlines of the ingot at the outset. Within this shell solidification gradually proceeds towards the centre, being accompanied by a corresponding gradual shrinking outwards of the metal as it solidifies, while the space left is successively filled up with liquid metal from within. As soon, therefore, as the upper surface of the ingot is crusted over so that no more metal can be poured in, a cavity will be formed within the ingot, the situation of which will depend, in the first place, on the action of the law of gravity. This cavity, or, as it is commonly called, "pipe," is generally met with in the upper part of the ingot. The normal position of the pipe depends, however, on the mode and conditions of cooling, and the variation will be greater or less according to whether anything occurs to prevent this process taking its regular course.

Iron and steel contract in cooling, but during solidification they appear to expand. During the first moments of solidification and expansion the outside is freezing and the inside slowly contracting; later the shell contracts, while the inner portion may be slowly expanding, and being incompressible it resists and may tear the outside. Later, when the shell has grown cooler, and is gradually contracting, the centre is expanding, and the intermediate metal is contracting. After a time the intermediate metal overtakes and begins to outweigh both the contraction of the slowly cooling shell and the expansion of the central portion, producing a cavity or "pipe."

Blow-holes.—Ingot steel absorbs gases which partly combine with the iron, in the same manner as the other constituents, so as to form a real alloy. The gases thus absorbed consist principally of hydrogen, nitrogen, and carbonic oxide, while the amount absorbed depends in the first place on the temperature at which the steel was finished. The capacity of the iron to absorb them increases with a rising temperature, although the chemical composition is not without its influence. The presence of silicon and manganese will increase the capacity. During the casting operation a partial decomposition of the moisture of the air always takes place, and the dissociated hydrogen combines with the flowing metal; also the formation of carbonic oxide may occur within the mould, due to the action of carbon on any oxide present. This carbonic oxide for the most part escapes, the remaining part forms blow-holes.

The alloys of iron with gases are not of a permanent character, and there is always a tendency to dissociation as soon as the temperature of the metal has fallen sufficiently to allow of their escape, part of the gases pass away, while another part remains and forms blow-holes. Little gas escapes after a crust is formed on the surface, hence the formation of blow-holes depends to a great extent on whether the evolution of gases sets in before or after a top crust of metal is formed. The longer the cooling of the ingot the more readily will the gases escape. If sufficient silicon and manganese are present, the metal will cool down without evolution of gas. If the percentage of these elements is low, gases escape at an early stage of the cooling process.

Various devices have been introduced for consolidating steel ingots, and diminishing the injurious effects of blow-holes. Mushet cast a head of metal on the ingot

by means of a clay tube, with a view to preventing blow-holes. Whitworth & Co. formerly submitted the metal while fused to great pressure, by means of a powerful hydraulic press. The mould is lined with refractory material and constructed so as to allow of the free escape of gases during the compression. The idea of subjecting the ingots to great pressure was described by Bessemer in 1856, but such methods are now seldom used, on account of the expense. Mr. Jones of Pittsburg introduced a method of admitting high-pressure steam at the top of the ingot. A steam drum was fixed to the ingot-crane, having a number of cocks and india-rubber connecting pipes, corresponding to those of the moulds. When the moulds were filled, caps were fastened on, and steam admitted for 5 minutes at a pressure of 80 to 150 lbs.; mild steel requiring the higher pressure. The steam cools and hermetically seals the tops of the ingots, and also consolidates the steel, probably by ejecting the enclosed gases. Krupp of Essen used liquid carbonic acid instead of steam. Very strong iron bottles containing the liquid under great pressure are connected with the feeding hole, and when the cock is opened the expansion of the acid in changing from the liquid to the gaseous state exerts a pressure of 52 atmospheres. By heating the bottle to 200° C., previous to opening the cock, the pressure is increased to 800 atmospheres. Williams employs a mould, one of whose inner faces is concave. As soon as the shell of the ingot has solidified he opens the mould, and slips a plano-convex pressure plate between the mould and the ingot. The two sides of the mould are now gradually forced together by hydraulic pressure. The compression may be applied before or after the metal has passed to the plastic state. The former has little effect, as gases can and will escape from a liquid without compression. It may increase the

quantity of gas retained in the steel, the supersaturation of which occurs at the moment of solidification. Plastic compression may squeeze out the gases from the liquid interior through the crust of metal at the top. If gas remains the pressure may diminish the size of the cavities that contain it, or it may cause its re-absorption and dissolution. If the pressure is released too soon the gases may again escape. Blow-holes are found chiefly near the top of a solidified ingot. Holding steel for some time in a molten state before casting lessens the formation of blow-holes. Crucible steel may be allowed to remain for an hour in the crucible with advantage, so as to kill it. It is then said to be "dead melted."

Treatment of Steel Ingots.—Steel is not piled like iron for reheating, but cast into an ingot of the proper size for the production of the required bar, plate, rail, etc. The hot ingots are usually conveyed from the moulds to a reheating furnace (see Figs. 76-78), and were formerly extended by the steam-hammer before rolling, but this is now considered objectionable, and they are therefore passed directly through the "cogging-" or roughing-rolls, then reheated and rolled in the finishing-rolls to the required section. For rails, the blooms after "cogging" may be finished right off without reheating, being rolled in long lengths and then cut into rails of the required length, by circular saws. This reduces the amount of waste from the crop-ends, as a fewer number of rough ends require to be cut off, than when the rails are made in short lengths.

Steel Castings.—Steel castings were in existence 50 years ago, but until the last few years the production was but small. The introduction of the Bessemer and Open-Hearth processes opened up a means of making such castings in large quantities at a moderate cost. In 1885 Robert

invented his converter, with a side blast, and made excellent castings, and in fact opened up practically a new industry, which has been extending ever since. Many difficulties had to be overcome by steel founders before success crowned their efforts. In the first place the melting point of steel is very high, about 1400° to 1500° C., and in working the metal still higher temperatures are required. This high melting point and the shrinkage the steel undergoes in cooling, which may be as much as 1·8 to 2 per cent., according to the composition, increase the difficulties. If the mould offers too great a resistance to this contraction the casting is liable to crack or become crooked. One important point is to prepare a suitable refractory sand for moulding. It is composed of quartz sand, burnt bricks, and some clay to make it plastic. To overcome the difficulty of the great shrinkage a number of contrivances have to be resorted to, such as ribs to strengthen weak parts, the early removal of the core, which opposes the contraction of the metal, etc. Another improvement is the subjecting of the pieces to a sudden cooling during annealing. Castings at 1000° C. are cooled to a temperature of 600° C., by this means their power of resisting shock is increased, and they become more elastic and tough. The improvements in the basic open-hearth have greatly assisted the steel founder, especially in the production of large castings, such as for armour plate and artillery. Steel castings are prepared from patterns, after the usual foundry practice, but the moulds are generally dried before the metal is run in.

The prevention of blow-holes is of course an important item, and this is accomplished by the use of manganese and silicon where possible, but in mild steel, which must only contain small quantities of these elements, a little aluminium is advantageous. Shrinkage holes are also a source of trouble. In order to get the castings solid they should cool

from the bottom upwards, and there should be sufficient metal in the head to supply all deficiencies. For this method of cooling it is necessary for the largest parts of the casting to be nearest the runners. Castings of fairly uniform thickness give the best results.

Unannealed cast steel resembles burnt steel in its fracture, and its behaviour resembles that of an over-heated forging. The proper annealing of large castings takes nearly a week. Different articles require different amounts of carbon. Steel for pinions and hammer dies requires 0·6 per cent. of carbon; miscellaneous gearing from 0·4 to 0·6; general machinery castings less than 0·4; and castings subject to great shocks should not contain more than 0·2 per cent. Hulls and gun carriages contain from 0·2 to 0·3 per cent. of carbon. Steel castings to stand the same stress as iron ones need only be one-third as heavy, if they are large. Steel is now taking the place of iron in gearings, hydraulic cylinders, engine cross heads, pistons, rolls, spindles, coupling boxes, hammer heads, dies, and castings for ships. The metal used in Russia in 1893 for stem and stern posts of a gunboat is given by S. Kern as follows:

	Carbon.	Manganese.	Silicon.	Phosphorus.	Sulphur.
Stem, -	0·13	0·50	0·27	0·03	0·02
Stern, -	0·15	0·45	0·25	0·04	0·02

The mechanical tests showed respectively 32 and 35 tons per square inch tensile strength, and elongations of 12·3 and 11·2 per cent. on 8 inches. Silicon-spiegel, containing 10 per cent. silicon and 12 per cent. manganese, was used for producing soundness. The metal retained about 0·3 per cent. of silicon.

Special Tool Steels.—The tool steel made by the Bethlehem Steel Co. for cutting at high speed, almost

regardless of the temperature, is said to contain 0·5 per cent. of chromium, and 1 per cent. of tungsten or molybdenum, or a mixture of the two; in some cases the amount runs to 5 or 6 per cent. The tools made from such a steel are first heated to 940° C., and in some cases to 1000° C., and then suddenly cooled to below 840° C. in a lead bath, and the temperature may be kept stationary for a few minutes between 370° and 670° C., or they may be reheated to those temperatures. A fusible slag is used to protect the metal from oxidation during heating. This is termed the Taylor-White process. If very hard metals have to be worked the alloy consists of at least 3 per cent. of chromium, 6 per cent. of tungsten, and 3 per cent. of molybdenum, the carbon varies, but 0·85 is usual. Such steel requires to be heated to a high temperature for hardening, and is therefore liable to crack.

Steel Rails.—Rails are subjected to a heavy percussive stress, and the harder the steel the longer the wear. But increase of hardness also brings with it increase of brittleness, especially if the phosphorus be too high, hence there is a limit beyond which it is unsafe to go. However, steel rails are now made generally harder (that is higher in carbon) than formerly. A medium hardness is therefore best, as it gives a good life to the rail without great liability to break. Silicon is another element which promotes brittleness, and this element should be low. The higher wheel loads now used on our large railways require greater hardness in the rails, or the ends are liable to be crushed. The carbon is now increased up to 0·5 per cent., the manganese to 1 per cent., the silicon to 0·1 per cent., but the phosphorus must not exceed 0·075 per cent. As explained in another section the bad effect of phosphorus is intensified by an increase of carbon, and when steel is used with as high as 0·6 per cent. of carbon, as in some

modern American rails, the phosphorus and silicon can only be present in very minute quantities, or the safety of the rails will be dangerously impaired. Mr. Sandberg,[1] rail inspector of the Swedish state railways, found that 80 lb. rails with 0·6 per cent. carbon flew into pieces with less than half of the specified "tup test," while those with 0·45 per cent. stood the drop of one ton falling from a height of 20 feet.

A rail, being subject to repeated blows in practice, is generally tested by a drop test. This consists of the weight of one ton falling 15 feet with a light rail, and 20 feet with a heavy one. For light railways in this country a 56 lb. per yard rail was stipulated by the Board of Trade, a maximum axle load of 10 tons, and a maximum speed of 25 miles per hour. With regard to the safe maximum of 0·45 per cent. carbon for rails it should be remembered that below this amount soft ferrite prevails over the pearlite. With about 0·45 per cent. the ferrite and pearlite are in equal quantities, and above 0·45 the pearlite predominates. The pearlite contains a very hard constituent, which therefore increases the hardness of the steel; so that we may consider that when the carbon is below 0·45 per cent., ductility predominates over hardness, and above 0·45, hardness predominates over ductility. Sir Lothian Bell is inclined to the belief that the fracture of rails is due more to mechanical causes than to chemical composition.

The manufacture of American rails at the Edgar Thompson works is described by Prof. Turner in a paper to South Staff. Inst., 1902. The ingots, after being removed from the soaking pits by an electric crane, are carried by an electrically driven endless rope to a universal mill. The ingot here makes two passes, being raised, lowered, or moved by a table worked by hydraulic power. The mill is

[1] *Jour. Iron and Steel Inst.*, No. 2, 1898.

a continuous one, there being no reversal. The bloom so produced is now mechanically conveyed to the hot shears for the purpose of being cut into two pieces. The larger one of these pieces is of definite length, and is intended to be rolled into two rails, each 33 feet in length, and weighing about 80 lbs. to the yard. The smaller piece, or crop end, is rolled in a separate smaller mill for the production of lighter rails.

The large pieces, which are rolled in No. 1 mill, on leaving the hot shears, travel on live rollers to the reheating furnace, into which they are charged with an electrically driven pusher, and when ready, are withdrawn by a similar mechanical apparatus through opposite doors on the other side of the furnace. Each furnace is provided with nine doors on each side, so as to take all the blooms from a heat, and there are, in all, five such furnaces. From the reheating furnace, the bloom passes to the rolls, which are arranged in sequence, in a line, so that the material passes straight forward from the heating furnace to the railway car. The first set, or roughing rolls, are three high, and here the steel makes five passes, after which it is taken by live rollers to the second, or intermediate rolls, which are also three high, where it again makes five passes. The rail is now taken to a cooling table, where it is allowed to remain and cool in the air somewhat, this special treatment being known as the Morrison-Kennedy system, the object being to develop the most suitable internal molecular structure. Incidentally, too, it is stated that this process leads to the formation of a scale of a peculiar thickness and character which readily peels off when the rail is again rolled, so that the finished rail has a smoother and cleaner surface than usual. After the rail has thus been permitted to cool in the air for about a minute and a half, and the proper temperature has been attained, it passes to the

finishing rolls, which are two high, and through which it only passes once, and then to the yard. The average production of this single mill is about 1000 tons in twelve hours; but this output, large as it appears in contrast to British practice, has been exceeded in this mill.

Returning now to the smaller pieces, or crop ends, these are taken on a small electrically driven trolley to the smaller or No. 2 mill, to be rolled into lighter rails, weighing about 30 lbs. to the yard. The pieces are first reheated in a natural-gas fired regenerative furnace, into which they are charged by the aid of an electrically driven ingot pusher. This smaller furnace is arranged so that one slab enters at each door, and the whole of the charging and withdrawing is accomplished by one apparatus, which is worked by a youth. The metal, when hot, is passed in succession through three sets of rolls, each three high, and it is never once touched by hand throughout its journey, as it is passed from one set of rolls to another by a fork-like appliance, which works with great regularity. The rails are ultimately hot sheared into three lengths, each 30 feet long. This smaller mill produces about 300 tons of light rails in 12 hours, the total production of the two mills being from 1300 to 1500 tons per shift, and each mill works 12 shifts, each of 12 hours, per week

CHAPTER XXIV.

MECHANICAL TESTS AND PROPERTIES.

THE value of different varieties of iron and steel, for many purposes, is determined by submitting them to certain mechanical tests, such as tensile, transverse, and crushing stresses; by the amount of elongation before rupture, and by their limits of elasticity. Some brands are tested by their malleability and toughness. For Admiralty requirements, iron ship-plates of the first class must have a tensile strength of twenty-two tons per square inch lengthways, and eighteen tons per square inch crossways. Plates one inch thick and under must be capable of being bent hot, without fracture, through an angle of 125° lengthways of the grain, and through 90° crossways. In the cold, one inch plates must bend through an angle of 15° along the grain, and through 5° across the grain, without fracture. Half-inch plates are required to bend through angles of 35° and 15° respectively.

Rivets, which should be made of the toughest wrought iron, or mild steel, should be capable of being bent double in the cold without cracking, and the heads hammered, when hot, until the diameter is two and a half times that of the shank, without fracture on the edges. Mr. Boyd has shown that rivets, made of Open-Hearth steel, are stronger and tougher than iron ones.

Angle-iron may be tested hot by being bent as in *A*, *B* (Fig. 117), or one flange cut off and bent in the cold as in *C*.

Tee-iron may be tested when hot by bending it into the form *D*, and by treating it in the cold as *C*.

Z and ⌴ or channel-iron may be tested by bending when hot as in *E*, *F*, and when cold as in *C*.

G represents a piece of Landore-Siemens steel plate doubled fourfold without fracture. *H* represents a piece of Open-Hearth half-inch round bar steel formed into a knot $2\frac{1}{4} \times 1\frac{1}{2}$ inches without fracture.

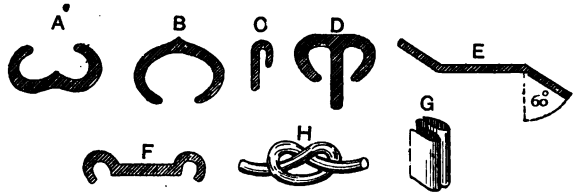


FIG. 117.

The physical tests to which iron and steel are subjected are usually certain defined alterations in shape, as previously indicated, or endeavours to produce fracture, the stress required being carefully determined.

Stress is the term applied to any force, either of extension or compression, and tends to produce an alteration of form.

Strain is the term applied to the alteration of form produced by the action of a stress, and within certain limits, varying in different bodies, is proportional to it. The limit in any case where this proportionality ceases is termed the "limit of elasticity."

Elasticity.—This is that property of matter in virtue of which a body requires force to change its bulk or shape, and necessitates a continued application of the force to maintain the change, and recovers its original form when the force is

removed. If a body completely recovers its shape, when the force which has caused a change of form is removed, it is termed a perfectly elastic body. In this sense all fluids are perfectly elastic. Solids, on the contrary, are generally imperfectly elastic, but the more homogeneous the body is the more perfectly elastic it is likely to be. This is the case with metals. As a rule they will bear considerable derangement of form and yet recover their shape; but at a certain point, varying for each metal, and with the physical condition of the metal, there is a limit to this alteration of form with subsequent recovery. This is termed the limit of elasticity. In general, parts of structures are so proportioned as to carry their loads without risk of exceeding their elastic limits. The elastic limit is made the basis of all estimates by most French engineers, while the ultimate strength is taken by German, English, and American engineers. If a metal is impressed beyond this limit the change of form becomes permanent, and permanent set takes place. Within the limit of elasticity the amount of strain produced in a metal is practically proportional to the applied stress. Beyond the limit of elasticity this proportionality ceases, and the strain is much greater than before for a given stress. The load which produces this permanent set is said to be the measure of the elastic strength of a metal, for, although it may not break, it is permanently altered. If a metal could be lengthened or shortened equally by equal stresses after the limit of elasticity had been passed, there would be some stress which would stretch it to double its length or shorten it to zero. This stress, expressed in pounds per square inch of a bar of metal, is termed the Modulus of Elasticity.

Tenacity or Tensile Strength is the power of resisting rupture by the action of a tensile stress. The molecules of different bodies are held together with varying degrees of

force, and the tensile force required to effect their separation depends upon the strength with which they are held together. In determining the tensile strength of a metal the chief points to decide are: the tensile stress the metal can sustain without rupture; the limit of its elasticity, the elongation per cent. on a bar one square inch of section, and the reduction of area at the broken part. Sometimes it is

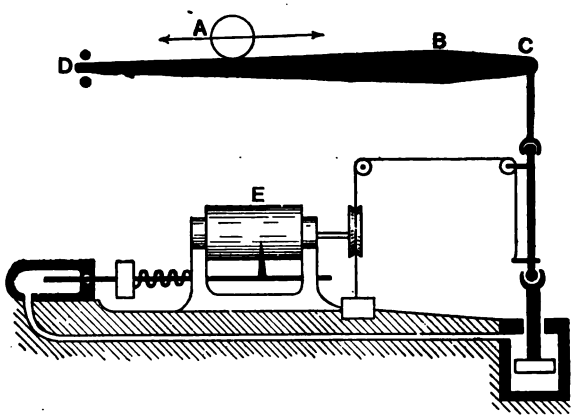


FIG. 118.

desirable to obtain the strain within the limit of elasticity. Iron and steel are elastic bodies, and admit of the application of a considerable force before breaking, but in ordinary cast iron it is much less, and the limit of elasticity is low. The elastic limit in any given quality of iron or steel will depend partly on the mechanical treatment it has undergone, but if such treatment raises the elastic limit in one direction it is done at the expense of the elastic limit in the opposite direction; thus, if the elastic limit be raised for tension it is lowered for compression. The above-mentioned properties are determined by means of a testing machine. Wicksteeds' is represented diagrammatically in

Fig. 118. It contains a single lever. A movable poise *A* measures the load, while the pressure is applied by a ram. The ratio of *BC* to *BD* is 50 : 1. The poise is 1 ton, so that when at *D* it balances 50 tons at the end of *C*.

E is a revolving drum which is actuated by the thread attached by clips to the specimen which is being elongated. The pencil, which is actuated by pressure in the hydraulic press, has an axial motion proportional to the stress. A stress-strain diagram is thus obtained.

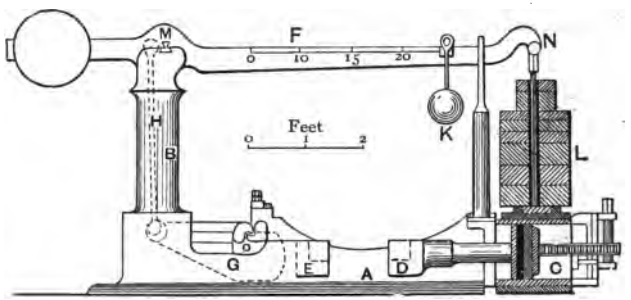


FIG. 119.

Testing machines have two pairs of jaws, in which the test-piece is held, one pair being connected with the head of the ram of a hydraulic cylinder, and the other end with a lever carrying weights, by which the tensile stress exerted by the hydraulic power is measured. Some machines have the jaws and test-piece so arranged as to produce a pull in a vertical direction, while in others the jaws are made to work horizontally.

Fig. 119 represents a simple 30-ton machine, in which *A* is the cast-iron bed-plate, *B* a hollow standard supporting a beam or lever *F* at the top. *C* is the hydraulic pump, the ram of which is attached to a pair of jaws *D*. The opposite pair of jaws *E* are connected with the levers *F* and *G* by a connecting rod *H*. The lever *F* carries a

jockey-weight K, and also a rod and plate for supporting additional weights L, which represent tons and half tons. The beam F is supported on a knife-edge at M, the longer arm being balanced by a dead-weight. The length of the arm MN is 56 inches, and the distance of the knife-edge from the point of attachment of the rod H 2 inches, which

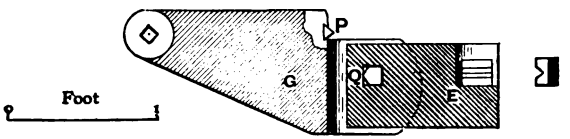


FIG. 120

gives a leverage of 28 to 1. When the jockey-weight K is placed at No. 20 of the scale, it exerts a pull of 1 ton on the jaws E. The bell-crank lever G (Fig. 120) is also supported on brackets O; it is 15 inches long, and the vertical distance from the point of attachment to the knife-edges P is 3 inches, giving a leverage of 5 to 1. The pull is exerted through a third knife-edge shown at Q. Thus the total advantage gained by the compound lever is $28 \times 5 = 140$; therefore a weight of 8 lbs. suspended at L represents 1120 lbs. or $\frac{1}{2}$ ton. The movable grips or dies which hold the test piece are shown in Fig 121. They are parallel and serrated on their inner faces, but tapered at the sides to an incline of 1 in 6, causing the grip to be tightened in proportion to the pull, and loosened when the stress is removed. The hydraulic ram has a stroke of 8 inches.

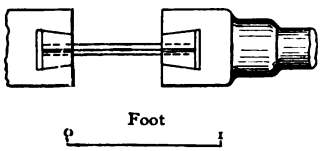


FIG. 121.

To test a bar of iron or steel $\frac{3}{4}$ inch diameter and 8 to 12 inches long, it is placed in the grips, the length between the

grips is measured, and pressure applied by the hydraulic pump, the jockey-weight being at zero of the scale. A weight representing $2\frac{1}{2}$ tons is placed on the seat, and the jockey-weight gradually moved towards the point marked 20. If this is found insufficient to balance the pressure exerted by the pump, and the bar shows no signs of breaking, the jockey-weight is returned to zero and an additional weight added. The above process is then repeated, and so on until the bar breaks, when the weights

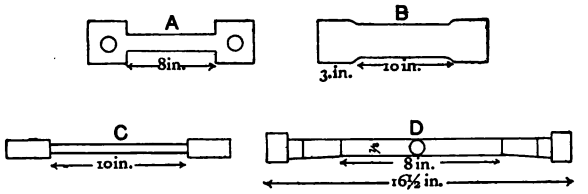


FIG. 122.

added representing tons, and the position of the jockey-weight representing fractions of a ton, are noted, the pump being worked continuously, except during the intervals of moving the weights. The bar is then measured, in order to determine its amount of elongation between two marks previously made on the bar, and its reduction of area at the point of rupture.

In making comparative tests it is essential that all test-pieces should be of the same length and thickness, for a thin section will give a proportionately higher resistance per unit of area than a thicker one. The proportional elongation before fracture is greater with short pieces than with long ones.

The shape and length of the test-piece, as well as the method of holding it, also has an influence on its apparent strength. The old method of holding specimens was by means of pins (Fig. 122, *A*), and if the pin is sufficiently large,

and the hole exactly in the axis, the plan is satisfactory, but expensive. It is usual now to use shackles with wedge-shaped grips for plate specimens, using test-bars as shown in *B*. With materials which are brittle the test-bar must be recessed, but with ductile materials it is often left plain; nevertheless the recessed form is best, and the distance between the shoulders should be eight or ten inches.

C shows the form of round bars for friction grips with V-shaped recesses, which are simple and convenient, but the bar is liable to break at the shoulder, and would be better if made as in *B*. The defect of a clip like this is, that the specimen may slip a little, being held less tightly on the one side than on the other; the specimen then breaks by tearing. Many specimens are prepared with a screw-thread chased on the ends, on which nuts are screwed, these being held in a clip; this plan is expensive, and is objectionable if the screw-threads are not accurate. Professor Unwin considers the official German test-bar (*D*) the best form of specimen for tension experiments. The test-bar is formed with collars, under which are placed two halves of a ring having a spherical bearing-surface, the only objection being its expense.

Cast-iron.—The tensile strength of cast-iron is sometimes determined for special purposes, but it is much more common to test it for transverse stress and the amount of deflection without breaking. The test-bars may be cast separately or cast on the casting itself. When test-bars are cast separately they are usually cast hotter than the castings they are to represent, and this has an influence on the strength, which is in favour of the test-bar. It is desirable to take the test-bar from the metal in bulk, and not from the cupola, in order that the bar may be of the same composition as the casting. Buchanan states that in all his experiments the bar cast separately is the

strongest. The bar cast on, or furthest from the casting, is less strong, and the bar nearest to the casting is the weakest. He concludes that the weakest bar is therefore most nearly allied to that of the casting itself. When the iron is required for casting columns and similar work which have to support great weights, its crushing strength is then required to be known. The test-pieces for transverse tests are generally cast 3 feet 6 inches long, 2 inches deep, and 1 inch wide, thus allowing a distance of 3 feet between the supports. Now the strength of a rectangular bar, supported at the ends and loaded at the centre, is inversely as the distance between the supports, and directly as the width, and the square of the depth. $S = \frac{wd^2}{l}$. Therefore a bar 1 foot long between the supports, and 1 square inch in section, would have a strength equal to $\frac{3}{4}$ths that of the standard test-bar mentioned above.

Transverse Testing Machine.—A 40 cwt. machine for testing bars for transverse stress is represented in Fig. 123. It consists of a bed-plate *A* of cast iron, which supports a hollow square pillar *B*. On the top of this rests a wrought-iron lever *C*, balanced on a knife-edge *D*, and adjusted by means of a counterpoise *E*. Inside the pillar is an eye-bolt *FF*, through which the test-piece is placed, the extremities of which pass through the movable dogs or eye-piece *GG* (Fig. 123 A), which may be fixed 3 feet apart, or less if desired. Near the top of the eye-bolt at *H* (Fig. 123 B) is another knife-edge which supports the eye-bolt, and between the knife-edge and the screw is placed a distance-piece, which prevents the point of the screw *J* from touching the knife edge when pressure is applied to the screw by means of the hand-wheel *K*.

The arm *CL* is graduated to represent cwts. and fractions of a cwt., and carries a heavy sliding-weight *M*, moved by

a small friction-roller. When the centre of the weight points to 0 it is just counterpoised by the weight *E*, and when it is at the mark 40 it exerts a pressure of 40 cwts.

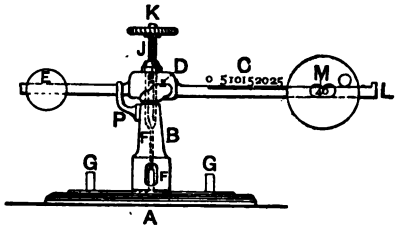


FIG. 123.

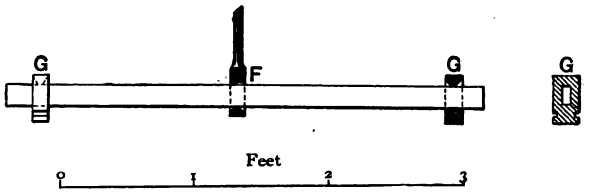


FIG. 123A.

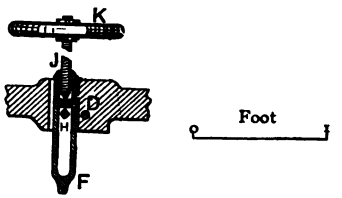


FIG. 123B.

on the centre of the test-bar. The movement of the lever *C* is limited by the check-bracket *P*.

The horizontal distance from the knife-edge *D* to the line passing through the centre of the screw *J*, along which the pressure is exerted, is $1\frac{3}{4}$ inches, and the distance from 0 to

40 of the scale is 35 inches, which gives an advantage of 20 as regards leverage. The weight *M* weighs 2 cwts., and this multiplied by 20 equals 40 cwts.

To test a bar of cast-iron it is placed in the position shown in Fig. 123 A. The centre of the weight *M* pointing to 0, the screw is made tight and the sliding-weight moved a little away from zero, which causes the arm *C* to dip. The screw is again tightened, which produces a pull on the centre of the bar and restores equilibrium in the lever *C*. The weight is again moved along the scale and the screw again tightened. The amount of deflection is now measured by means of a rule and calipers, and the process repeated with frequent measurements until the bar breaks, when the breaking weight is noted.

Professor Turner[1] gives the following tensile strengths of unusually good cast-iron:

Tensile Strength in Tons per Square Inch.	15·7	18·2	17·1	16·8	16·4	16·7	15·2	18·5
Graphite, - -	1·62	—	—	—	—	—	—	—
Combined carbon,	0·56	0·36	0·58	0·52	0·40	0·32	0·30	0·78
Silicon, - -	1·96	1·29	1·50	1·13	1·33	1·34	1·63	1·31
Phosphorus, -	0·28	0·56	0·47	0·41	0·70	0·09	1·10	0·29
Sulphur, - -	0·03	0·06	0·07	0·06	0 05	0·14	0·12	0·08
Manganese, -	0·60	1·00	1·00	1·33	0·65	1·38	1·29	1·51

The average composition shown in the above table may be taken as the best composition for cast iron with maximum tensile strength, combined with soundness and good working qualities. By increasing the silicon the metal becomes softer and more fluid. By diminishing the silicon the transverse and crushing strengths, together with the tendency to chill, are increased.

[1] *Engineering Magazine*, May, 1902. *Jour. Soc. Chem. Indus.*, Vol. vii. p. 200.

In order to test the properties of cast iron, Keep[1] of Michigan cast the pieces in green sand, with yokes or chills of ⊓ shape inserted in such a manner that the bars are cast with their ends against a chill of cast iron. The bars are $\frac{1}{2}$ inch square and 12 inches long, the chills being made $12\frac{1}{8}$ inches apart to allow for shrinkage. A thin bar 12 inches × 1 × $\frac{1}{8}$ inch is cast in the same manner.

1. **Shrinkage** is measured by placing the bars in the above yokes and inserting a graduated wedge between the end of the bar and the chill.

2. **Transverse strength** is determined by means of a lever machine.

3. **Depth of chill** is ascertained by breaking the end of the bar in the direction of its length, and recording the point where the chill ceases.

4. **Resistance to impact** is measured by a pendulum hammer, the height of fall being increased until the bar breaks.

5. **Fluidity** by using a pattern 1 foot long and 0·06 inch thick, and running the metal from one end. The length to which it flows indicates its fluidity.

6. The grain of the iron is examined by a lens.

7. Some irons cool irregularly and become crooked. The crook is determined by a 12-inch flat bar, on one side of which a rib is cast, and, when cold, the distance the rib has pulled away the ends of the bar from a straight line is taken as a measure of the crook.

It should be noted that the quantity of total carbon in cast iron is of secondary importance, as a moderate alteration in the graphite makes little difference, but the proportion of combined carbon is all important, as a little difference will alter the strength and hardness of the casting.

[1] *South Staffordshire Inst.*, 1888, and Turner's *Iron*, p. 239.

The effect of chemical composition on the mechanical properties of iron and steel is shown by the following tables by Thurstans:

No.	Elongation.	Elastic Limit in Lbs. per Square Inch.	Ultimate Strength in Lbs. per Square Inch.
1	29·67	26,500	43,000
2	25·50	34,500	55,000
3	34·33	28,500	52,000
4	20·83	26,000	60,000
5	12·00	49,400	69,700
6	21·67	50,473	71,300
7	20·17	44,000	71,000
8	19·50	47,800	83,100
9	2·75	50,000	94,500
10	3·58	50,500	101,000
11	1·00	65,190	101,400
12	9·75	50,500	112,400
13	8·17	50,500	113,100
14	11·08	51,000	118,900
15	10·08	61,900	122,200
16	8·08	68,100	125,500
17	7·33	75,300	135,300

Pure iron has a tenacity of 38,000 to 39,000 lbs. per square inch.

Each 0·01 per cent. carbon added raises that figure 1,200 lbs. with acid steel, and 950 lbs. with basic steel.

Manganese affects acid steel but slightly and adds 85 lbs. per one per cent. in basic steel.

Phosphorus adds tenacity with acid steel 890 lbs. per one per cent.; with basic steel 1,050 lbs.

But the above figures will be modified according to the manner in which the steel has been worked. These deductions were made from the behaviour of soft steel, but are probably applicable to harder metals.

CHEMICAL COMPOSITION.

No.	Carbon.	Sulphur.	Phosphorus.	Silicon.	Manganese.	Copper.	Cobalt.	Nickel.	Remarks.
1	0·009	0·009	0·084	0·163	0·020	0·023	0·021	0·016	
2	0·057	0·007	0·179	0·219	0·063	0·013	0·075	0·055	
3	0·130	0·029	0·045	0·011	0·192	0·002	—	—	
4	0·234	—	0·039	0·084	—	0·014	0·036	0·057	Antimony, 0·115.
5	0·234	0·012	0·034	0·105	0·184	0·022	0·016	0·021	
6	0·401	0·006	0·032	0·085	0·112	0·008	0·021	0·026	
7	0·463	0·002	0·020	0·121	—	0·003	0·018	0·018	
8	0·577	0·026	0·108	0·108	0·185	—	—	—	
9	0·639	—	0·007	0·154	0·050	0·008	—	—	Chromium, 1·044.
10	0·691	0·028	0·065	0·028	0·459	0·022	—	—	
11	0·756	0·043	0·104	0·074	0·465	0·346	0·052	0·120	
12	0·806	—	0·019	0·172	0·193	—	—	—	
13	0·873	—	0·015	0·134	0·046	0·003	—	0·023	
14	0·923	0·002	0·014	0·141	0·036	0·003	—	0·018	
15	0·996	—	0·019	0·157	0·245	—	—	—	
16	1·121	—	0·023	0·206	0·269	—	—	—	
17	1·328	—	0·017	0·246	0·262	—	—	—	

Tenacity of Steel Wire.—Wire cannot be made from hard steels, only from the softer varieties.

Crucible Steel (0·165 inch diameter) gives 125,000 to 200,000 lbs. per square inch tensile strength and an elongation varying from 7 to 21 per cent.

Bessemer Steel gives 150,000 to 178,000 lbs. per square inch tensile strength and elongates 20 to 40 per cent.

Open-Hearth Steel varies from 175,000 to 182,000 lbs. per square inch tensile strength and elongates 22 to 42 per cent.

Steel-wire Rope, 7 inches diameter, broke at 118 tons per square inch, 6 inches diameter broke at 92 tons, and 5½ inches diameter broke at 75 tons.

TENACITY OF STEEL CASTINGS.

Composition.			Tenacity in Lbs. per Square Inch.	Elongation per cent.
C.	Si.	Mn.		
0·26	0·26	0·41	68,096	27·5
0·30	0·22	0·63	69,440	24·0
0·35	0·23	0·61	80,640	21·5
0·43	0·27	0·75	105,036	13·1
0·50	0·40	0·66	101,248	5·0
0·55	0·40	1·00	103,712	9·8
0·77	0·46	0·67	75,262	1·5
0·96	0·62	0·64	85,792	1·0

It is important that all such castings should be annealed or serious loss of strength will be incurred. The Open-Hearth is generally preferred to the Bessemer process for steel castings.[1]

Prof. Arnold made a number of alloys of practically pure iron and various elements and rolled them into test bars of

[1] See Thurstans, *Iron and Steel*, Part II.

0·564 inch diameter. On testing they gave the following results :[1]

Alloy.	Per Cent.	Carbon per Cent.	Total Impurity.	Elastic Limit in Tons per Sq. Inch.	Maximum Stress in Tons per Sq. Inch.	Elongation per Cent.	Reduction of Area per Cent.
Iron, - -	99·87	0·04	0·13	14·39	21·77	47·0	76·5
Carbon, -	1·35	1·35	0·44	46·53	57·50	5·0	5·6
Nickel, -	1·51	0·11	0·30	22·45	26·80	35·3	62·0
Manganese,	1·29	0·10	0·50	22·72	32·16	35·0	65·0
Copper, -	1·81	0·10	0·29	30·80	34·80	30·5	62·2
Chromium, -	1·10	0·17	0·28	19·75	27·18	40·0	72·1
Tungsten, -	1·41	0·08	0·30	20·00	27·24	42·5	76·6
Aluminium,	1·85	0·03	0·16	17·00	27·04	35·0	63·7
Silicon, -	1·94	0·08	0·29	20·40	31·68	36·0	62·4
Arsenic, -	1·57	0·04	0·16	17·75	27·10	28·5	34·1
Phosphorus,	1·36	0·07	0·17	28·98	28·98	—	—

The effect of carbon in increasing the tensile strength of iron may be summarised as follows :

TENSILE STRENGTH IN TONS PER SQUARE INCH.

Carbon, per cent., -	0·1	0·2	0·3	0·4	0·5	0·6	0·8	1·0	1·3
Tons per square inch—									
Upper limit, - -	35	40	45	50	55	60	75	85	58
Lower limit, - -	25	30	33	35	38	40	45	50	45
Elongation, per cent.—									
Upper limit, - -	29	25	23	21	12	10	6·0	—	—
Lower limit, - -	18	15	12	10	8	5	1·5	—	—

The compressive strength rises with increase of carbon up to a certain limit, about 1·2 per cent. Thus :

Carbon.	Ultimate Compressive Strength in Lbs. per Square Inch.	Elastic Compressive Strength in Lbs. per Square Inch.
0·3	47,513	40,666
0·6	84,827	52,666
0·9	95,207	58,000
1·2	102,173	61,666

[1] *Jour. Iron and Steel Inst.*, No. 1, 1894.

Strength of Hardened Steels.—With carbon below 0·5 per cent. water quenching raises the tensile strength greatly. With carbon over 0·75 per cent. it either lowers the tensile strength or raises it but slightly. Oil quenching generally raises the tensile strength. To get the maximum tensile strength in mild steels they should be cooled rapidly. With the higher carbon steels the maximum tensile strength is obtained by cooling the steels more slowly, hence they should be quenched in oil. With regard to elongation, water quenching lowers the percentage of elongation the more and oil quenching the lesser of the two. The elongation of high carbon steels is more reduced by hardening than that of the lower carbon steels. The elastic limit is raised by hardening, generally in a greater ratio than that of the tensile strength. The following table shows Kern's results of testing tool steel:[1]

	Carbon. Per Cent.	Tensile Strength. Tons per Square Inch.	Elongation in 2 Inches Per Cent.	Reduction of Area. Per Cent.
Crucible steel, -	0·60	45	12	30
Do., -	0·80	58	6	14
Do., -	0·90	62	5	12
Open-hearth, -	0·60	42	15	50
Do., -	0·80	50	12	28
Do., -	0·90	55	10	23

Besides carbon, the crucible steel contained 0·52 manganese; 0·16 silicon; 0·03 sulphur and 0·03 phosphorus per cent. The open-hearth steel contained 0·42 manganese; 0·08 silicon; 0·01 sulphur; and 0·04 phosphorus per cent. Generally speaking, hard open-hearth steel has less tensile strength than crucible steel of the same carbon content, and shows a marked tendency to temper badly after hardening.

[1] *Chem. News*, Vol. 83, p. 181.

Owing to the high percentage of manganese in open-hearth steels the cutting edge of tools made of such steels is liable to crumble.

American Standard Tests and Specifications.—These tests are the result of the recommendations of a committee, appointed in 1898, to standardise specifications of iron and steel. The processes of manufacture are summarised in the following tables by Mr. A. L. Colby:[1]

Specification for	Open-hearth Process.	Crucible Process.	Bessemer Process.
Steel castings, - - -	Open-hearth	Crucible	Bessemer
Do. axles, - - - -	do.	—	—
Do. forgings, - - -	do.	Crucible	Bessemer
Do. tyres, - - - -	do.	do.	—
Do. rails, - - - -	do.	—	Bessemer
Do. splice-bars, - - -	do.	—	do.
Structural steel for buildings,	do.	—	do.
Structural steel for bridges and ships, - - -	do.	—	—
Boiler plate, and rivet steel,	do.	—	—

Ingots must be kept in the vertical position in pit-heating furnaces: no bled ingots must be used: sufficient material must be removed from the top to insure soundness.

With regard to annealing, internal strains may be removed by it. Slow cooling from the initial temperature of casting, rolling, or forging must not be a substitute for annealing, as this enlarges the grain and therefore weakens the steel.

Steel castings must not be over 0·4 per cent. carbon and 0·08 per cent. phosphorus, and not over 0·05 per cent. sulphur.

Steel axles, not more than 0·05 per cent. phosphorus and sulphur.

[1] *Jour. Iron and Steel Inst.*, No. 2, 1900.

Steel forgings, not more than 0·04 per cent. phosphorus and sulphur, and if nickel steel, not more than 3·75 per cent. of nickel.

Steel tyres, the limit is 0·8 manganese, 0·2 silicon, and 0·05 per cent. phosphorus and sulphur.

Structural steel for buildings should not exceed 0·10 per cent. phosphorus.

Structural steel for bridges and ships, not more than 0·08 phosphorus and 0·06 per cent. sulphur.

Boiler plate, not more than 0·3 to 0·5 manganese, and 0·04 per cent. of sulphur and phosphorus.

Steel splice bars, not more than 0·15 carbon, 0·03 to 0·6 manganese, and 0·01 per cent. of phosphorus.

STEEL RAILS OF WEIGHT PER YARD.

	Carbon.	Manganese.	Silicon.	Phosphorus.
				Not over
50 to 59 + lbs.	0·35 to 0·45	0·70 to 1·00	not over 0·2	0·1
60 to 69 + ,,	0·38 to 0·48	0·70 to 1·00	do.	0·1
70 to 79 + ,,	0·40 to 0·50	0·75 to 1·05	do.	0·1
80 to 89 + ,,	0·43 to 0·53	0·80 to 1·10	do.	0·1
90 to 100 + ,,	0·45 to 0·55	0·80 to 1·10	do.	0·1

In all the specifications, except for steel rails, limits in tensile strength are specified, in order to ensure the necessary strength in the material. The elastic limit is, however, the true index of resistance to working stresses. In material uniformly heated before rolling, a large number of tests have proved that the elastic limit practically never falls below 50 per cent. of the tensile strength. As its accurate determination is impossible in rapid commercial testing, the tensile strength is relied upon to indicate the elastic limit, with which information the stresses which may be successfully carried can be safely computed.

LIMITS IN PHYSICAL PROPERTIES.

		Tensile Strength in Tons per Square Inch.	Yield Point in Tons per Sq. Inch.	Elongation per Cent.	Contraction of Area per Cent.	Bending Test D = Diameter.[2] T = Thickness.
Steel castings,	Tested castings: hard,	37·94	17·08	15	20	—
	Tested castings: medium,	31·25	14·06	18	25	90° $D = 2T$.
	Tested castings: soft,	26·78	12·05	22	30	120° $D = 2T$.
Steel axles,	Carbon steel,	35·71	17·85	18	—	—
	Nickel steel,	35·71	22·32	25	45	—
Steel forgings,	Low carbon steel,	25·89	12·95	28	35	180° $D = T$.
	Steel not annealed,	33·48	16·74	18	30	180° $D = 3T$.
Steel tyres,	Passenger engines,	44·64	—	12	—	—
	Freight engines and car wheels,	49·11	—	10	—	—
	Switching engines,	53·57	—	8	—	—
Structural steel for buildings,	Rivet steel,	23·32 to 26·78	13·39	26	—	180° flat.
	Medium steel,	26·78 to 31·25	15·62	32	—	180° $D = T$.
Structural steel for bridges and ships,	Rivet steel,	23·32 to 26·78	13·39	26	—	180° flat.
	Soft steel,	23·21 to 27·68	14·29	25	—	180° flat.
	Medium steel,	26·78 to 31·25	15·62	22	—	180° $D = T$.
Boiler plate, and rivet steel,	Flange or boiler steel,	24·55 to 29·02	14·73	25	—	180° flat.[1]
	Fire-box steel,	23·21 to 27·68	14·29	26	—	180° flat.[1]
	Extra soft steel,	20·09 to 24·55	13·39	28	—	180° flat.[1]
Steel rails,	—	—	—	—	—	—
Steel splice bars,	—	24·11 to 28·57	14·29	25	—	180° flat.

[1] These same bending tests are required after quenching. [2] D is diam. of the piece around which test is bent.

This table does not include the drop test required on castings, axles, tyres, and rails.

This table does not include variations in elongation allowed for thick and thin structural steels and boiler steel, nor tensile tests of full-sized eye-bars.

The elongations given for castings, axles, forgings, and tires are on 2″, the others are on 8″, gauged length.

Drop Test.—The specifications for axles, tyres, and rails require a drop test, generally a weight of 1 ton, and a test to destruction may be substituted for a tensile test in the case of unimportant castings. An axle must stand a certain number of blows from specified heights without rupture and without exceeding, as the result of the first blow, a given deflection. A tyre must stand, without breaking or cracking, successive blows from increasing heights until it shows a deflection equal to $D^2 \div (40T^2 + 2D)$, in which D is the internal diameter of the tyre, and T the thickness at the centre of the tread. A rail must not break or crack under a single blow on the head from heights in feet varying with the section of the rail, as follows:

Weight of Rail in Lbs. per Yard.	Height of Drop.
45 to and including 55	15
More than 55 do. 65	16
Do. 65 do. 75	17
Do. 75 do. 85	18
Do. 85 do. 100	19

Tests of Steel Axles and Tyres.

Axle.—4¼ inches diameter. Placed on bearings 3 feet 6 inches apart and tested by a blow of 1 ton falling 16 feet, and must stand 6 such blows without fracture, axle to be reversed after each successive blow.

1st blow, - - 6 inches deflection.
2nd do., - - $\frac{3}{16}$ do. from straight (axle reversed).
3rd do., - - 5$\frac{5}{8}$ do. deflection.
4th do., - - $\frac{9}{16}$ do. from straight (axle reversed).
5th do., - - 5$\frac{3}{8}$ do. deflection.
6th do., - - $\frac{7}{16}$ do. from straight (axle reversed).

TYRE.—Must stand compressing (by falling weight) 2 inches per foot of inside diameter.

1 ton weight,	2 feet drop,	- -	$\frac{1}{16}$	inch deflection.
do.,	4 do.,	- -	$\frac{1}{4}$	do.
do.,	6 do.,	- -	$\frac{1}{2}$	do.
do.,	8 do.,	- -	$\frac{9}{16}$	do.
do.,	10 do.,	- -	$\frac{3}{4}$	do.
do.,	12 do.,	- -	$1\frac{3}{16}$	do.
do.,	14 do.,	- -	$1\frac{5}{16}$	inches do.
	Total,	- -	$4\frac{1}{4}$	inches.

NOTE.—Above tyre is 2 feet outside diameter.

CHAPTER XXV.

MICROSCOPIC STRUCTURE OF IRON AND STEEL.

§1. THE study of the internal structure of metals by means of the microscope practically originated in the year 1864 with Dr. Sorby of Sheffield, who was the first to publish a paper on the peculiar microscopic structure of iron and steel. The idea apparently lay dormant until the year 1878, when Professor Martens in Germany contributed a paper on the "Microscopic Structure of Iron and Steel." He has since published the results of his various investigations, and may now be considered as one of the greatest authorities on the subject. Other workers, notably Messrs. Osmond & Werth in France, began to perceive the great possibilities of the new method, and devoted close attention to it with characteristic thoroughness and energy. This recognition of the importance and practical application of microscopic research brought back Dr. Sorby to the field with additional contributions on micro-metallography. In 1882 he delivered a lecture on the subject in the Firth College, and in 1886 to the Iron and Steel Institute, on the "Application of very High Powers to the Study of the Microscopical Structure of Steel." In the following year a similar paper was also contributed. In the meantime the subject was vigorously pursued in other countries, for we

find a paper by J. C. Bayles on the "Microscopic Analysis of the Structure of Iron and Steel" in the *Transactions of the American Institute of Mining Engineers for* 1883, and again in 1885 by F. Lynwood Garrison. In 1885 Messrs. Osmond & Werth contributed a paper on the "Cellular Structure of Iron and Steel," and in the same year Dr. Wedding read a paper to the Iron and Steel Institute on the "Properties of Malleable Iron, deduced from its Microscopic Structure." For the next ten years metallography was closely studied in France, Germany, and America, while during all this period extremely little notice of this work was taken by the British technical press, and as Mr. J. E. Stead remarks: "No person in the whole of Great Britain appeared to consider the matter of sufficient importance to notice until Professor J. O. Arnold commenced working at it about 10 or 12 years ago. Thus it will be seen that the infant science, born in Sheffield, has been for many years neglected in the mother country, and has been fostered abroad."[1] It is pleasing to have to record that this state of things no longer exists, and that Mr. Stead stands in the front rank of active and enthusiastic workers. He, as well as Professor Arnold, have already added immensely to our knowledge by their papers, not only of the structure of iron and steel, but of other metals and their interesting alloys.

The microscope is making its appearance in many of our large works, and industrial chemists and experts of different kinds are eager to embrace this new means of investigation. It must be clearly recognised that microscopic examination is not intended to, nor ever will replace chemical analysis or mechanical testing of metals. Its function is to add additional information of a kind which other methods

[1] Paper on "Study of Micro-Metallography," Cleveland Inst. of Engineers, 1895.

are incapable of yielding. Thus, in steel, ordinary chemical analysis will indicate the total quantity of carbon, combined and free, but will not reveal the presence of definite mineral constituents, such as ferrite, cementite, pearlite, martensite, and the manner in which they are associated in the steel. Again, in an alloy such as brass, chemical analysis will give the percentage of copper and zinc, but will not tell us how many different compounds or alloys exist in the main alloy, or whether any free metal is present. It will not reveal the internal structures, crystalline or otherwise, which so materially modify the physical properties, and will not alone prove the presence or absence of an eutectic. It is true that some of these properties may be discovered by other means, but even then the microscope is a valuable aid in confirming results brought out by other physical methods. In accordance with a suggestion made by Mr. Howe, mineralogical names have been given to the various constituents of iron and steel in order to facilitate their identification.

FIG. 124.

Ferrite (Fig. 124).—This is the free iron of Sorby. It consists of practically pure iron, and is the chief constituent of wrought iron and mild steel, in which it exists as polyhedral grains, of very irregular form. In general it decreases as the amount of combined carbon increases, and is practically absent from hard steels and white cast iron. Howe con-

siders the crystals to be interfering cubes or octahedra. It is also a constituent of pearlite, of which it forms about two-thirds the bulk. These crystals of carbonless iron are left white and brilliant when treated with a solution of iodine. Strong nitric acid also does not stain them. Ferrite may contain other elements which form isomorphous mixtures with iron. It is the softest constituent of iron and steel.

Cementite.—Carbon of normal carbide (Ledebur), reheated carbon (Osmond and Werth), carbon of cementation (Caron). This is the intensely hard carbon of Sorby. It was first clearly discovered in steel made by the cementation process. It is hard, and stands out in relief when soft steel is polished, but is practically absent from highly hardened steels. Dr. Müller and the late Sir Frederick Abel independently isolated it, and found it to contain 93·33 per cent. of iron and 6·67 of carbon, which corresponds to the chemical formula Fe_3C. It is soluble in strong boiling sulphuric or hydrochloric acids. It remains bright after being polished and treated with iodine solution. Being very hard it stands out in relief when the steel is polished with the finest rouge on parchment laid on wood. A similar compound carbide is found in manganese steel, which has been submitted to cementation. Cementite will scratch glass and felspar, but not quartz. It has therefore a hardness of about 6·5. Free cementite does not occur in

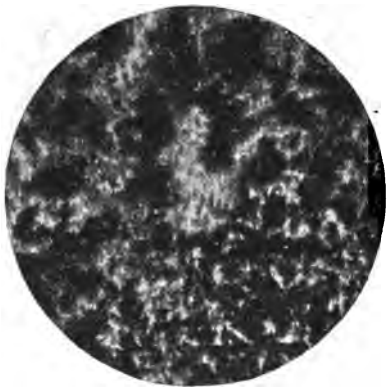


FIG. 125.

normal mild steel. It is an essential constituent of pearlite. Fig. 125 is a section showing cementite and pearlite.

Pearlite (Fig. 126).—This is the pearly constituent of Sorby, and is made up of an intimate mixture of ferrite and cementite. It is found in steel which has been slowly cooled from a high temperature, and may be lamellar or granular in structure. Steel that contains 0·89 per cent. of carbon is composed wholly of pearlite. It generally consists of alternating plates of ferrite and cementite, or cementite and sorbite; or grains of cementite embedded in ferrite or sorbite. Baron Jüptner considers that the cementite of pearlite consists chiefly of a carbide, having the formula ($Fe_{12}C_4$), but that the sorbite perhaps contains Fe_9C_3. It appears that cementite and ferrite or sorbite usually unite in certain proportions, as far as possible, to form pearlite, so that any excess of ferrite or cementite remains free. Thus pearlite may be accompanied by either free cementite or ferrite, but not usually by both together in the same region. Hence as the proportion of combined carbon increases in unhardened metal from nil, we have first ferrite, then ferrite with a portion of pearlite, which increases up to 100 per cent. at 0·89 per cent. carbon, and then diminishes as the proportion of combined carbon increases, being replaced more and more by free cementite. Thus, high carbon steel, say with 1·8 per cent. carbon,

FIG. 126.

contains little pearlite and much cementite. Sorby considers that white cast iron consists of about two-thirds pearlite and one-third cementite; while spiegel-eisen contains about equal quantities of each. If steel is long exposed to a high temperature, the pearlite draws together and separates itself in more perfect crystals from the ferrite or cementite that accompanies it. If, however, the pearlite be initially associated with graphite, its cementite apparently tends to split up into graphite and ferrite at a moderately high temperature. Pearlite may be coloured dark by iodine solution, and its presence is best revealed when the steel is polished in relief, and treated with a filtered infusion of liquorice root in cold water. The laminae of pearlite are alternately hard and soft, the cementite being hard and the ferrite soft.

Sorbite.—This is a transition form, passing into pearlite, intermediate between troostite and pearlite, probably having the composition Fe_9C_8, and existing in a solution of iron. It may be simply unsegregated pearlite. Sorbite is obtained by a moderately slow cooling, as in the cooling of small samples in air. Also by quenching in water at the end of the recalescence period. It is tinted brown by etching in dilute acids, or in iodine solution. It is also coloured by a solution of liquorice root.

Troostite.—This is a transition form between martensite and pearlite, so that when a hardened steel has been partially annealed the martensite is only partially changed to pearlite, and then contains some troostite. According to Osmond, it is contained in steels of various carbon contents on quenching at certain temperatures. It is revealed by polishing the steel on parchment, moistened by a solution of liquorice root, or nitrate of ammonia, which turns it brown. It is softer and more readily acted on by acids, than martensite. By etching with an alcoholic

solution of hydrochloric acid (1 part hydrochloric acid in 100 parts of alcohol) martensite remains unaltered, while troostite is coloured dark. It is possibly a solution of the carbide Fe_9C_8 in iron.

Martensite.—This is the very hard substance of which hardened steel consists. It imparts a characteristic structure to polished and etched surfaces of hardened steel. The appearance is that of interlacing rectilinear fibres, roughly arranged in triangular shape, and which may be coloured by tincture of iodine. It is possible that ferrite and cementite unite to form martensite when the steel is highly heated, and the structure is retained when the metal is rapidly quenched. Professor Arnold affirms that martensite is not a constituent, but a crystalline structure developed at high temperatures. It is marked in saturated steels by preferential etching lines; in unsaturated carbon steels by striae of ferrite; and in supersaturated steels by striae of cementite. Osmond considers that martensite corresponds to the maximum amount of allotropic iron and hardening carbon that may be retained, by sudden cooling, in carburised irons in which the carbon contents of the mixed crystals do not exceed 1·1 per cent. before quenching. It is most readily obtained by the rapid quenching of small samples. It is very coarse in steel with 0·5 per cent. of carbon, and very fine in steel with 1 per cent. of carbon.

Austenite.—This term is applied by Osmond to a constituent of high carbon steels which is developed by very sudden quenching from a high temperature. It is softer and less magnetic than martensite, with which it is generally associated. The structure may be developed by polishing on parchment, moistened with liquorice solution, or nitrate of ammonia. The austenite remains white, while the martensite becomes brown, and often appears in a zigzag

form. The relative hardness is tested by scratching with a sewing needle. On account of its low degree of hardness, and because it is only stable at high temperatures, Baron Jüptner considers it to be a solution of elementary carbon

FIG. 127.

in iron. Fig. 127 shows a section containing austenite and martensite.

Hardenite.—According to Howe, this is understood to be martensite in the form of the eutectic solution. The term was first applied by Charpy to martensite with its maximum percentage of carbon (0·89), and Arnold claims that it has the chemical formula $Fe_{24}C$. In unsaturated steels the hardenite is accompanied by unsegregated ferrite, and in saturated steel the mass consists wholly of hardenite, while in supersaturated steels the hardenite is accompanied by unsegregated cementite.

Carbon.—As this is the most important element occurring in iron and steel it is necessary to know its different forms.

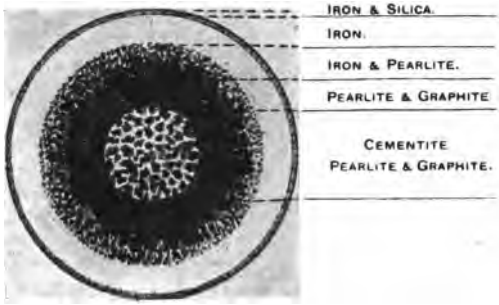


FIG. 128.

Carbide carbon is a name given to the carbon existing in cementite, and is synonymous with combined carbon.

Subcarbide is, according to Arnold, hardened steel containing 0·89 per cent. of carbon.

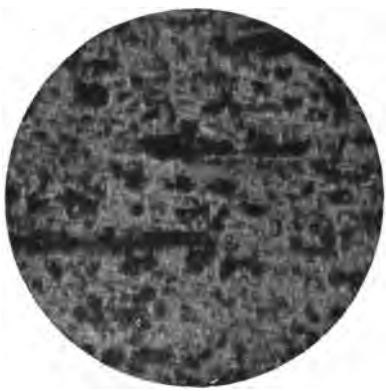


FIG. 129.

Annealing carbon; the apparently amorphous, finely divided carbon having some graphitic properties, which separates from white cast iron and from certain steels during prolonged annealing, and, according to Ledebur, from high carbon steel when it is raised to a red heat by rapid hammering. It is insoluble in dilute acids. Ledebur terms this temper carbon, the word "temper" having in Germany a different meaning

to what it has in England, and is expressed by the term annealing.

FIG. 130.

Graphite carbon is the form that separates out from highly carburised fluid irons, previous to, or during solidification.

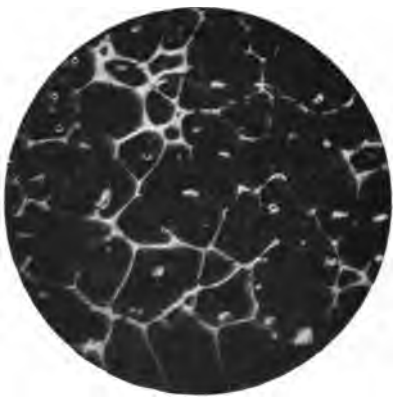


FIG. 131.

Missing carbon is a term applied by Howe to that part of the carbon in hardened and tempered steels which does

not give colour to the solution on dissolving the steel in nitric acid of 1·2 specific gravity.

The following examples, taken from the author's work on metallography,[1] will serve to indicate the general nature of microscopic structures:

Fig. 128 is a section of a round bar of malleable cast iron.

Fig. 129 is a longitudinal section of wrought iron, consisting chiefly of iron and slag.

Fig. 130 is a section of mild steel showing large crystals of ferrite in a matrix of pearlite.

Fig. 131 is a section of steel with 1·8 per cent. of carbon, showing cementite in a matrix of pearlite.

[1] *Metallography*, Hiorns (Macmillan & Co.), 1902.

CHAPTER XXVI.

CONDUCTIVITY AND MAGNETIC PROPERTIES.

Conductivity is the power different bodies possess of transmitting heat and electricity. The conducting power of copper is reduced 50 per cent. by the presence of 0·5 per cent. of iron, and a much smaller quantity renders it unfit for many electrical purposes. The conducting power of metals is diminished by a rise in temperature, and in metals that undergo no molecular change before fusion the increase of resistance is proportional to the temperature.

Prof. Barrett[1] has made an extensive series of experiments on the conductivities of various alloys of iron with other metals, and finds that the electric and thermal conductivities go hand in hand, and anything that causes a diminution in the electric conductivity also diminishes the thermal conductivity. His results show that the conductivity of iron is in all cases diminished by alloying it with other metals, even though the added metal be a better conductor than iron, except perhaps in the case of an alloy of iron and copper. The reduction of conductivity is not due to the greater specific resistance of the added metal, in fact the conductivity of the alloy appears to have no connection with the conductivities of the

[1] *Trans. Inst. of Elec. Engineers*, Feb. 13th, 1903.

constituents. Thus, aluminium is a much better conductor than nickel, yet an aluminium alloy of iron is a worse conductor than the corresponding nickel-iron alloy. Of all the alloys examined by Barrett, tungsten appears to reduce the conductivity the least. Carbon produces such a striking effect on the conductivity of iron, that, other things being equal, the determination of the amount of carbon present may be made in a sample of steel by this means.

The greatest reduction of conductivity, for a given percentage of the added element, is produced by the first increments of the elements added. As the alloy becomes richer in the added element the proportionate diminution of conductivity becomes less, and in the case of high resisting alloys, such as those of nickel and manganese, the difference between a 13 and 18 per cent. alloy is hardly perceptible. In most cases annealing diminishes the resistance of iron alloys, which are often much worse conductors in the hardened than in the annealed state. It is interesting to note that those alloys that are harder by slow cooling than by quick cooling, such as the 14 per cent. manganese steel, have a greater resistance in the slowly cooled state.

Magnetic Properties.—The magnetic susceptibility of pure iron is well known. It has very low hysteresis with high induction. The effect of alloying other elements with iron is to increase the hysteresis and to decrease the inductive capacity. In some alloys the magnetic susceptibility is almost nil. This is the case with manganese steel. Carbon plays a very important part in the magnetic properties of all iron alloys. In low manganese steel (3 to 4 per cent.) high carbon injuriously affects the magnetic properties; but in high manganese steels (over 10 per cent.) increasing the carbon improves the magnetic properties.

The degree of hardness agrees with the relative magnetic conditions. In two magnetic steels, with about 3·5 per cent. of manganese, but with different amounts of carbon, the one with the highest carbon was the hardest and much the worse magnetically. With an alloy of 10 to 11 per cent. manganese the reverse was the case. So that an otherwise non-magnetic steel may become magnetic by the simultaneous presence of high carbon.

Nickel, up to 8 per cent. increases the hardness and tensile strength of iron, but over 20 per cent. decreases it. Mechanical and magnetic softness go together here as elsewhere. Tungsten steel possesses high coercive force, and permanent magnets are made with steel containing 5 to 7 per cent. of tungsten. These alloys must be well annealed, as the remanence, coercive force, and hysteresis loss are much greater in the hardened condition. Chromium increases the magnetic hardness of iron, increasing the coercive force, and diminishing the magnetic permeability. Copper in iron has a much less injurious effect magnetically than chromium or manganese.

Silicon and aluminium have a softening influence on iron, and, up to a certain percentage, improve the magnetic properties of the alloys. An alloy with 2·5 per cent. silicon or aluminium with iron gives the most remarkable results magnetically, exceeding that of the best Swedish charcoal iron. Still more remarkable is the alloy of iron with 2·25 per cent. of aluminium; not only is the permeability greater, but the maximum induction in all fields up to 60 units is greater than that of any known magnetic body, including the purest iron. It may be that the effect of these elements, silicon and aluminium, is to combine with any oxygen, or reduce any oxide of iron present, and leave the crystals of iron pure and more uniform in texture.

For fuller information the reader is referred to the original paper.[1]

With regard to non-magnetic alloys of iron the following may be noted:

Iron.	Carbon.	Manganese.	Nickel.	Tungsten.
86·74	0·26	13·0	—	—
85·77	1·23	13·0	—	—
80·06	0·8	5·04	14·10	—
88·22	1·21	8·0	2·57	—
86·61	1·08	10·2	—	2·11

It will be seen from the above what a great change may be made by the addition of another element to a given alloy. Thus, high nickel steels are fairly magnetic, but an addition of 5 per cent. manganese may make them non-magnetic.

[1] *Trans. Inst. of Elec. Engineers*, Feb. 13th, 1903.

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